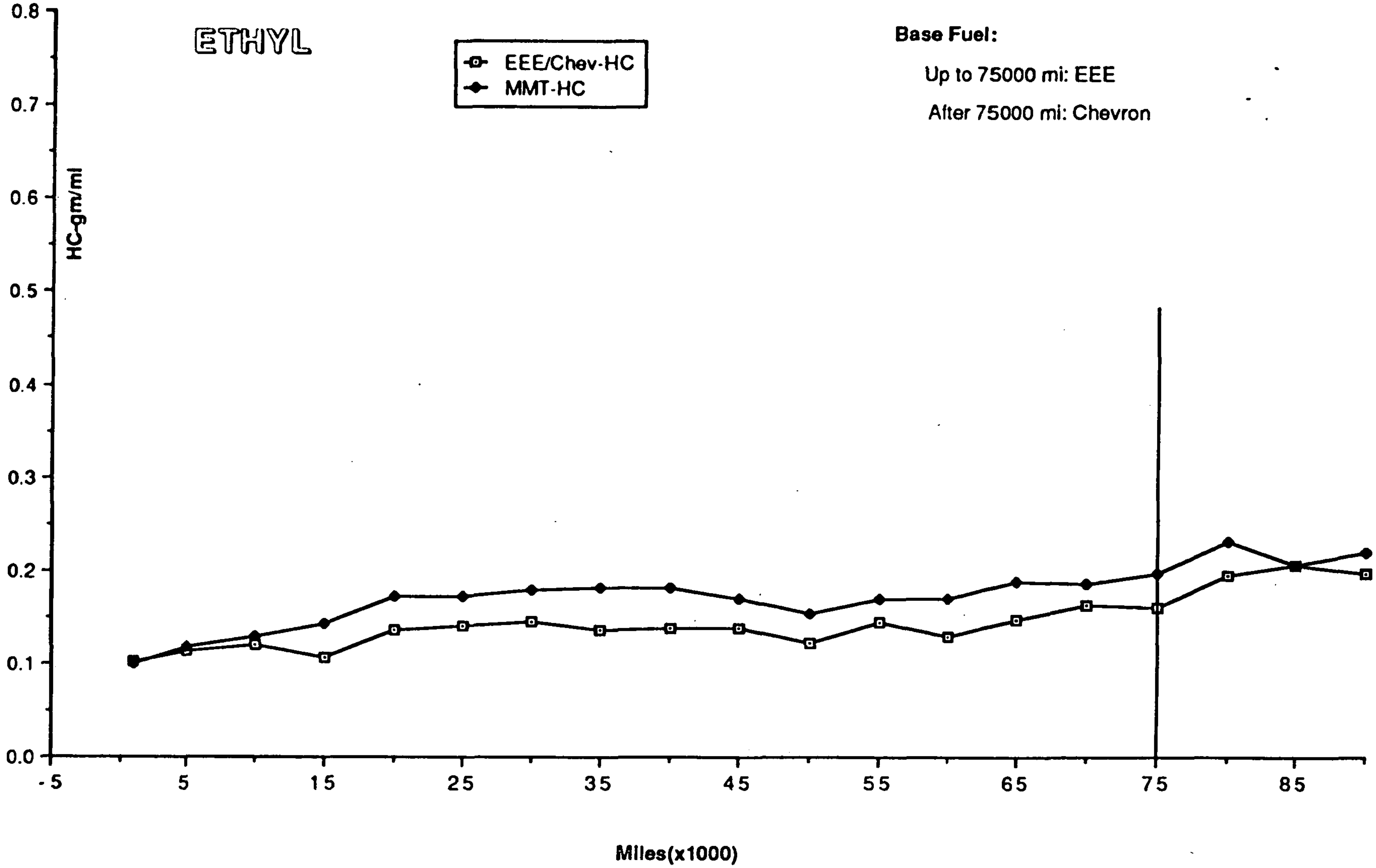
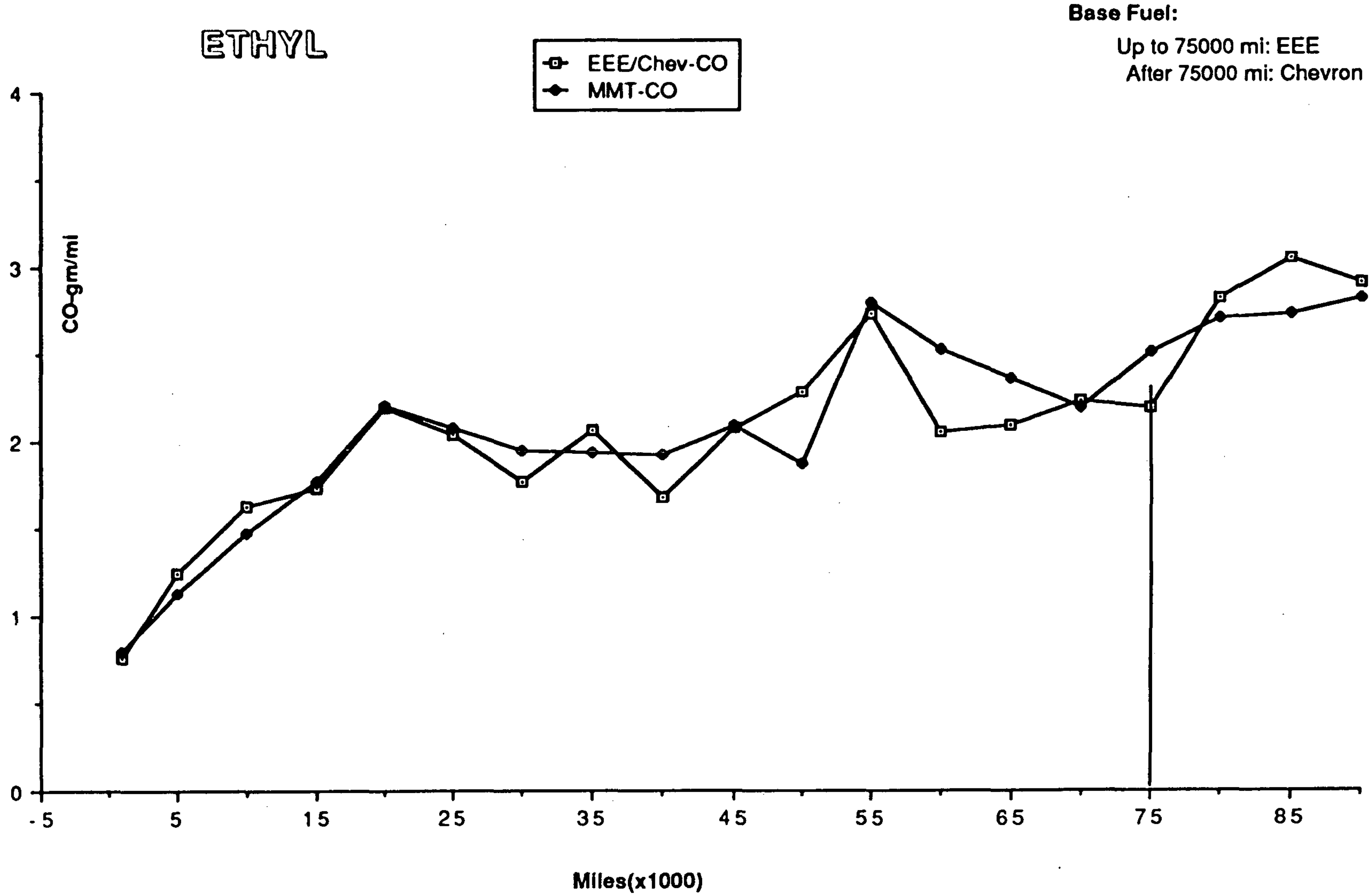
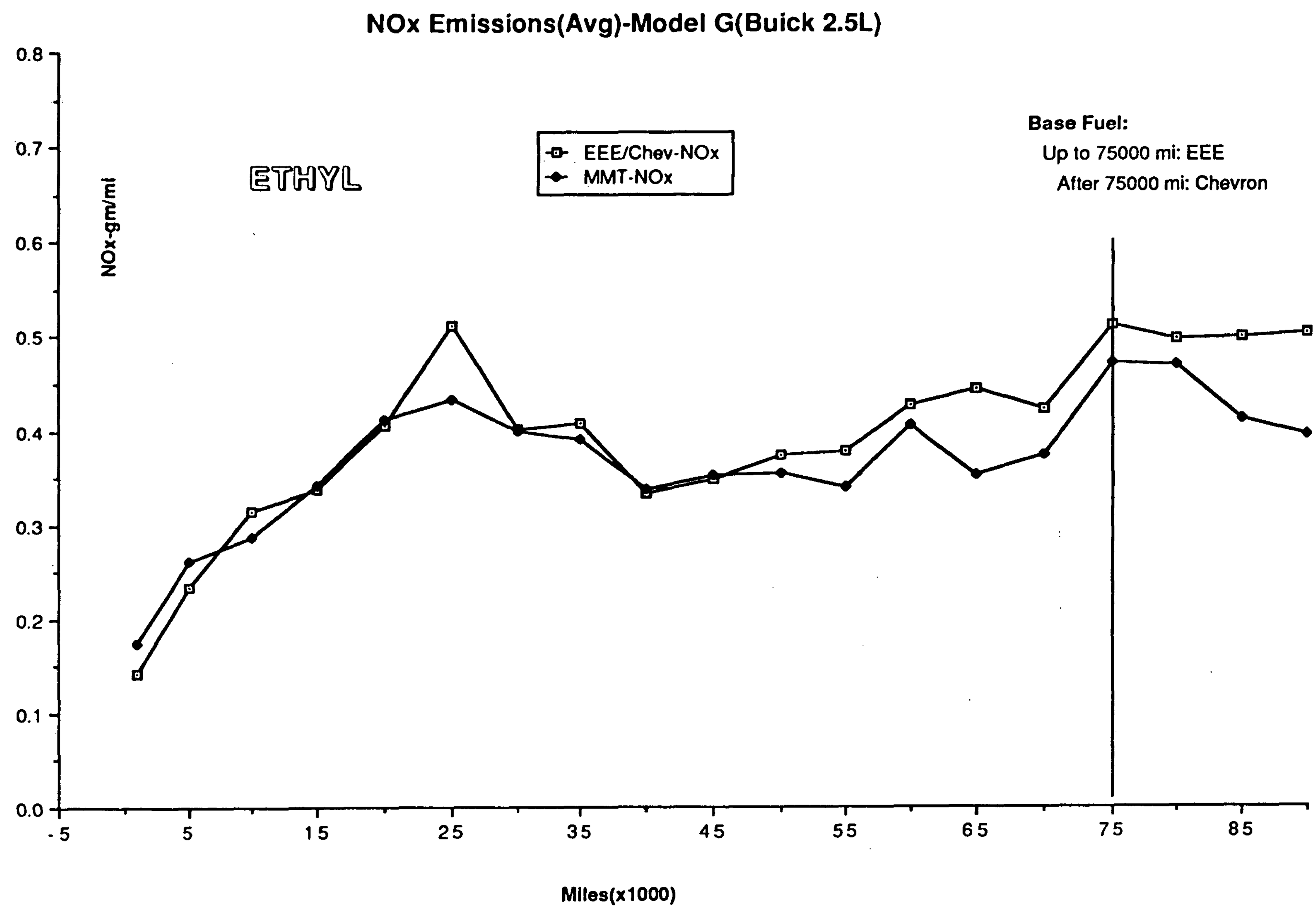
HC Emissions(Avg)-Model G(Buick 2.5L)



CO Emissions(Avg)-Model G(Buick 2.5L)

ETHYL




NOx Emissions(Avg)-Model G(Buick 2.5L)
ETHYL
EEE/Chev-NOx
MMT-NOx
Base Fuel:
Up to 75000 mi: EEE
After 75000 mi: Chevron
NOx-gm/mi
Miles(x1000)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-5
5
15
25
35
45
55
65
75
85

Emissions-Model G

Wed, Nov 13, 1991 1:54 PM

	Miles(x1000)	EEE/Chev-HC	MMT-HC	EEE/Chev-CO	MMT-CO	EEE/Chev-NOx	MMT-NOx	Remarks
1	1	0.101	0.100	0.758	0.789	0.142	0.173	Base Fuel:
2	5	0.113	0.117	1.243	1.131	0.234	0.261	Up to 75000
3	10	0.120	0.130	1.631	1.469	0.313	0.287	miles: EEE.
4	15	0.106	0.142	1.732	1.773	0.338	0.341	After: Chevron
5	20	0.136	0.172	2.191	2.207	0.405	0.412	commercial
6	25	0.140	0.173	2.033	2.077	0.511	0.432	
7	30	0.146	0.179	1.770	1.947	0.400	0.399	
8	35	0.136	0.182	2.058	1.939	0.408	0.391	
9	40	0.139	0.182	1.682	1.919	0.334	0.338	
10	45	0.138	0.171	2.075	2.091	0.347	0.353	
11	50	0.123	0.153	2.282	1.873	0.373	0.354	
12	55	0.146	0.169	2.737	2.794	0.377	0.339	
13	60	0.130	0.169	2.053	2.525	0.427	0.406	
14	65	0.148	0.189	2.084	2.356	0.443	0.353	
15	70	0.164	0.186	2.234	2.190	0.422	0.373	
16	75	0.161	0.197	2.198	2.511	0.512	0.471	
17	80	0.194	0.232	2.818	2.706	0.497	0.469	
18	85	0.206	0.207	3.054	2.732	0.499	0.411	
19	90	0.197	0.219	2.907	2.825	0.503	0.394	

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TECHNICAL MEMORANDUM

TO: Ethyl Corporation
FROM: Ralph L. Roberson, P.E.
DATE: November 19, 1991
SUBJECT: Review of Ford's Functional Analysis

INTRODUCTION

In comments submitted to the Ethyl Wavier Request Docket (No. A-91-46), Ford Motor Company describes the results of its emission control system functional analysis.[1,2,3] This technical memorandum examines Ford's functional analysis and concludes that it does not support the broad conclusion that Ford draws from the analysis. In particular, the results of the functional analysis do not, as Ford claims, "demonstrate that MMT [HiTEC 3000] has significantly impaired the function of emission control devices."

Ford's functional analysis consists of interchanging EGO sensors and catalysts between clear fuel vehicles and vehicles that accumulated mileage with the HiTEC 3000 fuel additive. Ford's testing sequence consisted of running three emission tests with interchanged EGO sensors, three with interchanged catalysts, and three with interchanged EGO sensors and catalysts. The emission tests conducted at 105,000 miles (prior to interchanging components) serve as baseline results. The results of Ford's analysis, expressed in terms of pollutant conversion efficiency are summarized in Table 1 (attached).

Based on the functional analysis results, Ford concludes, "[t]hese test

[1] Letter from D.R. Buist, Ford Motor Company, to U.S. Environmental Protection Agency, Air Docket (LE - 131), dated October 3, 1991.

[2] Letter from David L. Kulp, Ford Motor Company, to U.S. Environmental Protection Agency, Air Docket (LE - 131), dated October 28, 1991.

[3] Facsimile transmission from Tom Lasley, Ford Motor Company to Dave Kortum, U.S. Environmental Protection Agency, dated November 15, 1991.

results demonstrate that MMT [HiTEC 3000] has significantly impaired the function of emission control devices (EGO sensors and catalysts)."

The above-cited statement by Ford is simply incorrect because it mischaracterizes the test data. Ford's conclusion is that the "emission control device" is impaired; yet, Ford's discussion focuses only on its HC functional analysis for two Escorts (No. 315 and No. 316). However, Ford's data show that the NO_x conversion efficiency, as determined at 105,000 miles, for the clear fuel and HiTEC 3000 Escorts are 85.1 and 85.2 percent, respectively. These data do not suggest that either emission control device is "impaired." Corresponding values for CO conversion efficiencies are 74.8 and 72.6 percent. A 2 percent difference in conversion efficiency, at 105,000 miles, hardly proves that the HiTEC 3000 emission control device is impaired, especially in light of the fact that average CO conversion efficiencies for the four clear fuel vehicles are essentially equal to those of the four HiTEC 3000 vehicles.

DISCUSSION

Ford's results for HC conversion efficiency are not surprising. Assuming two vehicles have about the same engine-out emissions and one of the vehicles has lower tailpipe emissions than the other, the logical explanation is that one of the emission control systems is performing better than the other control system. Moreover, it is not surprising that emission control performance is somewhat portable. That is, if one interchanges the emission control systems, it would not be unusual to find (<u>assuming all other sources of variability are controlled for</u>) that lower tailpipe emissions follow the better performing emission control system. However, we disagree with Ford's conclusion that HiTEC 3000 is the only possible explanation for the differences in HC conversion efficiency. The fact is, each emission control system is unique and is influenced by a number of operating variables. If this were not the case, all vehicles with the same emission control technology system would have almost identical tailpipe emissions.

Table 1 shows the functional analysis results for seven vehicles. Four are for clear fuel vehicles that receive emission control components from vehicles that accumulated mileage with the HiTEC 3000 fuel additive, and three are for HiTEC 3000 vehicles that receive emission control components from vehicles that accumulated mileage on clear fuel. Focusing on HC emissions, one observes that three of four clear fuel vehicles show decreased conversion efficiency with HiTEC 3000 components, and three of three HiTEC 3000 vehicles show increased conversion efficiency with the clear fuel components. This result is expected, given Ford's underlying emission data, and is not a new finding from the functional analysis. That is, Ford's emission data show increased HC emissions for the HiTEC 3000 vehicles, and one would not expect the functional analysis to contradict this result -- especially when the functional analysis uses the 105,000 mile emission data as its baseline.

Based on data submitted by Ford to EPA,[4] we computed conversion efficiencies, at each mileage interval, for the eight vehicles tested by Ford. These results are presented in Tables 2, 3, and 4 (attached). We believe it is informative to examine the HC conversion efficiencies for the pair of clear-fuel Explorers (No. 305 and No. 307). At 5,000 miles, the HC conversion efficiency of these two vehicles differed by about 3 percent (94.6% versus 91.3%). At 105,000 miles, the HC conversion efficiency differed by almost 7 percent (89.9% versus 83.0 %). Thus, Ford's own data show a significant difference in HC conversion efficiency between the two clear fuel vehicles at the start of the test program and a marked difference in catalyst deterioration over the duration of the test program -- and HiTEC 3000 cannot be the explanation.

Moreover, we believe that if Ford were to interchange the emission control systems between Explorer No. 305 and Explorer No. 307, Ford would find that the difference in HC conversion efficiency tended to follow the individual emission control systems. That is, Explorer No. 305 would show a decrease in

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[4] Letter to Mary T. Smith, U.S. Environmental Protection Agency from David L. Kulp, Ford Motor Company, dated September 23, 1991.

HC conversion efficiency (perhaps approaching 83 percent) and Explorer No. 307 would show some increase in HC conversion efficiency. Obviously, HiTEC 3000 cannot be the cause or explanation for the 7 percent difference in HC conversion efficiency for these two Explorers. Some other uncontrolled variable (i.e., component-to-component differences or vehicle maintenance) must account for these differences in clear fuel conversion efficiencies.

Ford might attempt to rebut the above discussion by pointing to the differences in HC conversion efficiency between clear fuel Explorers and Explorers using HiTEC 3000. The HC conversion efficiencies presented in Table 2 superficially support this argument. However, we question the validity of the HC conversion efficiencies computed for Explorers using HiTEC 3000 because of the underlying tailpipe emission data. Explorer No. 306 experienced a number of problems that required unscheduled maintenance. For example, Ford reports a clogged fuel injector and a fouled spark plug at about 55,100 miles. Ford reports replacement of No. 2 fuel injector at 55,200 miles. At 105,000 miles, Ford's first four emission tests show incredibly high HC emissions (≈1.3 grams/miles). Ford discovered a cracked spark plug insulator, replaced the plug, and conducted six additional emission tests. Based on these six tests, HC emissions average about 0.66 grams/miles. Average HC emissions of 0.66 grams/mile reflect an increase of over 350 percent from the 55,000 mile measurements. We believe that the 105,000 mile measurements for Explorer No. 306 are much more illustrative of operational problems than of the effect of a fuel additive. Since Ford did not report any test results at 85,000 miles, we have no useful information on this vehicle after 55,000 miles.

The functional analysis results obtained by Ford for Explorer No. 306 add additional support to our belief that tests conducted at 105,000 miles reflect significant vehicle operational problems instead of emission control system deterioration. For example, baseline HC conversion efficiency for Explorer No. 306 is 80.5 percent. However, when the EGO sensor and catalyst from Explorer No. 306 are placed on clear fuel Explorer No. 305 and tested, HC conversion efficiency is found to be a respectable 89.5 percent (see Table 1).

This HC conversion efficiency is not consistent with either: (1) extremely high HC emissions reported by Ford for Explorer No. 306 at 105,000 miles, or (2) the conclusion drawn by Ford that HiTEC 3000 significantly impairs the operation of emission control systems.

Likewise, Ford reports a number of operational problems with the other HiTEC 3000 Explorer (No. 304) that could affect emissions. The significant increase (i.e., on the order of 1 gram/mile) in engine-out HC emissions subsequent to the 20,000 mile tests is more likely associated with operational problems than with the use of any fuel additive. While No. 304 shows a steady increase in HC tailpipe emissions through 85,000 miles, there is a significant decrease in HC emissions between 85,000 and 105,000 miles. Indeed, in contrast to a decrease in HC conversion efficiencies for the clear-fuel Explorers from 85,000 to 105,000 miles (i.e., 91.2 to 89.9 percent and 86.7 to 83.0 percent), the HC conversion efficiency for No. 304 showed a substantial improvement over the same mileage interval. Simply stated, we believe there are too many problems and questions associated with the data obtained for the two HiTEC 3000 Explorers to warrant further analysis.

CONSISTENCY OF FUNCTIONAL ANALYSIS

The underlying hypothesis of Ford's functional analysis is that all variables are controlled for except the effect of HiTEC 3000 on emission control systems. Escort No. 315, with a baseline HC conversion efficiency of 91 percent, exhibited a conversion efficiency 86.3 percent with the EGO sensor and catalyst from HiTEC 3000 Escort No. 316. The HiTEC 3000 Escort, with a baseline HC conversion efficiency of 84.2 percent, exhibited a conversion efficiency of 90.6 percent with the EGO sensor and catalyst from the clear-fuel Escort. The symmetry of the HC results appear to support the hypothesis; however, the CO and NO_x results contradict the hypothesis.

For example, the clear fuel Escort, with a baseline NO_x conversion efficiency of 85.1 percent, shows a conversion efficiency of only 81.6 percent with the

EGO sensor and catalyst from the HiTEC 3000 Escort. However, the baseline NO_x conversion efficiency for the HiTEC 3000 Escort is 85.2 percent. Thus, Ford's functional analysis suggests a decrease in NO_x conversion efficiency of 3.5 percent (85.1 - 81.6), which is not supported by its baseline data. This inconsistency indicates that Ford's functional analysis does not control for all variables except for the effect of HiTEC 3000. The CO functional analysis also produces inconsistent results. Both Escorts exhibit higher CO conversion efficiencies after the components are interchanged than either baseline conversion efficiency. The clear fuel Escort increases from 74.8 percent to 76.0 percent, and the HiTEC 3000 Escort increases from 72.6 percent to 75.2 percent. The only reasonable explanation is that the functional analysis is subject to operating variables (and measurement variability) in addition to the type of fuel used by the vehicles.

CONCLUSIONS

For the reasons discussed in this memorandum, we believe the conclusion drawn by Ford from its functional analysis is not supported by its test data. For example, the pair of clear fuel Explorers exhibit as large a difference in HC conversion efficiency as do the clear fuel and HiTEC 3000 Escorts No. 315 and No. 316 for which Ford conducted its functional analysis. The Explorer data clearly demonstrate that variables other than the use of HiTEC 3000 influence the performance of individual emission control systems. Moreover, the results obtained from the functional analysis for CO and NO_x conversion efficiencies are inconsistent with the findings and conclusion drawn by Ford from the HC conversion results. This inconsistency further suggests that use of HiTEC 3000 is not the only potential variable affecting the conversion efficiencies reflected in Ford's functional analysis.

TABLE 1. CONVERSION EFFICIENCIES FROM FORD'S FUNCTIONAL ANALYSIS

Vehicle	HC		CO		NOx	
	Baseline	Interchanged EGO & Catalyst	Baseline	Interchanged EGO & Catalyst	Baseline	Interchanged EGO & Catalyst
No. 315	91.0	86.3	74.8	76.0	85.1	81.6
No. 316	84.2	90.6	72.6	75.2	85.2	85.9
No. 317	89.6	87.1	71.7	N.R.	82.4	N.R.
No. 318	84.8	86.9	69.7	62.5	83.7	80.3
No. 305	89.9	89.5	71.1	71.3	91.0	92.2
No. 306	80.5	91.8	63.0	84.8	89.8	80.2
No. 307	83.0	77.0	62.2	61.1	91.9	91.9
No. 304	76.0	N.R.	66.0	N.R.	86.8	N.R.

N.R. Data necessary to compute conversion efficiencies not reported in Ford's submission to EPA.

TABLE 2. HC CONVERSION EFFICIENCY BASED ON FORD TEST DATA.

FORD ESCORTS

Mileage	CLEAR		HiTEC 3000	
	#315	#317	#316	#318
5K	95.0	94.4	95.7	93.4
20K	92.5	91.1	92.6	88.1
55K	89.9	89.2	84.8	85.4
105K	91.0	89.6	84.2	84.8

FORD EXPLORERS

Mileage	CLEAR		HiTEC 3000	
	#305	#307	#304	#306
5K	94.6	91.3	91.4	94.1
20K	94.2	90.2	89.6	93.3
55K	92.1	85.7	84.2	94.4
85K	91.2	86.7	72.7	--
105K	89.9	83.0	76.0	80.5

TABLE 3. CO CONVERSION EFFICIENCY BASED ON FORD TEST DATA.

FORD ESCORTS

	CLEAR		HiTEC 3000	
Mileage	#315	#317	#316	#318
5K	88.6	88.6	89.0	85.6
20K	82.6	83.5	81.6	79.4
55K	76.0	78.9	75.1	81.4
105K	74.8	71.7	72.6	69.7

FORD EXPLORERS

	CLEAR		HiTEC 3000	
Mileage	#305	#307	#304	#306
5K	89.1	85.8	85.7	89.0
20K	85.8	83.0	79.6	85.3
55K	77.1	69.8	79.6	88.1
85K	74.4	72.1	64.1	--
105K	71.1	62.2	66.0	63

TABLE 4. NO_x CONVERSION EFFICIENCY BASED ON FORD TEST DATA

FORD ESCORTS

Mileage	CLEAR #315	CLEAR #317	HiTEC 3000 #316	HiTEC 3000 #318
5K	90.6	90.4	92.3	90.7
20K	90.0	89.6	90.4	88.9
55K	86.9	86.0	87.1	85.7
105K	85.1	82.4	85.2	83.7

FORD EXPLORERS

Mileage	CLEAR #305	CLEAR #307	HiTEC 3000 #304	HiTEC 3000 #306
5K	96.6	94.4	93.2	96.2
20K	95.5	94.8	92.5	96.8
55K	93.8	88.5	95.8	77.5
85K	93.1	87.9	88.3	--
105K	91.0	91.9	86.8	89.8

SwRI 08-4068

EFFICIENCY EVALUATION OF 24 USED CATALYTIC CONVERTERS

by

Melvin N. Ingalls

-- Revision A --

FINAL REPORT

Prepared for

Ethyl Corporation
Health and Environment Department
451 Florida Street
Baton Rouge, LA 70801

November 1991

SOUTHWEST RESEARCH INSTITUTE
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FOREWORD TO REVISION A

At the request of Ethyl Corporation, the Final Report for SwRI Project 08-4068, "Efficiency Evaluation of 24 Used Catalytic Converters," dated July 1991, has been revised. The purpose of this revision was to change some CO emission light-off times listed in Tables 4 to 27 of the original final report as "0.0" seconds, to indicate that these times were, in fact, not obtained for some reason. This revision changes tables that showed a light-off time of "0.0" from the low range CO instrument (low CO), when in fact, the 50 percent conversion point was greater than the full scale reading of the low CO instrument. In this revision, rather than showing "0.0" for these cases, "--" is used to indicate that there was no time read for this instrument. This revision also changes to "--", some low CO and CO instrument 50% conversion times that were listed as "0.0" for other reasons. In the course of this effort, the CO light-off times in Tables 15 and 17 were discovered to be incorrectly stated in the original report, and are corrected in this revision. These changes are only for the CO emission light-off times from the light-off tests, and do not affect any other emissions or results from other test conditions. The tables changed, and the reasons for the changes, are shown below.

TABLE NO.	EMISSION INSTRUMENT	PARAMETER CHANGED	REASON
4 to 6	low CO	50% light-off time deleted	50% point off-scale
10 & 11	CO	50% light-off time deleted	instrument malfunction
13	CO	50% light-off time deleted	instrument malfunction
14	low CO	50% light-off time deleted	50% point off-scale
15	low CO CO	50% light-off time corrected 50% light-off time corrected	incorrect reading incorrect reading
16	low CO	50% light-off time deleted	instrument malfunction
17	low CO	50% light-off time corrected	incorrect reading
18 & 19	low CO	50% light-off time deleted	50% point off-scale
20 & 21	low CO CO	50% light-off time deleted 50% light-off time deleted	50% eff. not achieved 50% eff. not achieved
22	low CO	50% light-off time deleted	50% point off-scale
23	CO	50% light-off time deleted	instrument malfunction
24 to 27	low CO	50% light-off time deleted	50% point off-scale

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I. INTRODUCTION

Twenty-four used catalytic converters furnished by Ethyl Corporation were evaluated for efficiency and light-off time on a slave engine. This work was conducted in response to an Ethyl Corporation letter request of December 4, 1990, and subsequent telephone discussions. A copy of the letter and its attachments are included in the Appendix A, together with the SwRI proposal prepared in response to that request. The work described herein was conducted by the Department of Emissions Research (DER) of Southwest Research Institute (SwRI) at their laboratory in San Antonio, Texas. This report describes the test cell, slave engine, emissions measured, converters tested, test procedures used, and the results of the tests performed.

II. EQUIPMENT, FUEL, AND INSTRUMENTATION

A. Test Cell

All testing was conducted in Cell No. 6 of SwRI's Department of Emissions Research. This cell is configured for catalyst aging and evaluation. Two engines, a 350 CID Chevrolet and a 7.5 liter Ford, are available for catalyst aging. Another 350 CID Chevrolet gasoline engine is installed in the test cell for light-off and efficiency evaluations. The load absorbers for the engines are eddy current dynamometers capable of absorbing up to 175 horsepower at 6000 rpm. The test cell has the necessary instrumentation to measure exhaust emissions before and after the converter being tested.

B. Slave Engine

The Chevrolet 350 CID engine used for catalyst evaluations is a heavy duty model equipped with a stock 1990 Camaro electronic port injection system. Control of the fuel injection to adjust air fuel ratio setting is provided by a laboratory fuel injection system capable of a wide range of air fuel ratios. The fuel control is Model IC 5160 Fuel Injection System manufactured by Intelligent Controls, Inc. of Novi, Michigan. SwRI modified the fuel injection control system to permit the air fuel ratio to be cycled at frequencies from 0.25 to 2 hertz. For this project the fuel control was set to vary the air fuel ratio plus or minus 1/2 A/F ratio at frequency of 1 hertz.

The engine exhaust system is configured especially for catalyst evaluations. The amount of engine exhaust that flows through the converter test section is adjustable, to permit a wide range of space velocities. A heat exchanger is installed in the exhaust piping to permit a range of catalyst inlet temperatures without changing engine conditions. There is a quick acting diverter valve ahead of the converter test section, to permit the engine and exhaust conditions to be set without having exhaust flow through the test converter. For a simulated light-off test, this valve diverts the engine exhaust away from the converter until the start of the light-off test, then the exhaust is quickly switched to the converter. A schematic of the exhaust piping is shown in Figure 1.

C. Fuel

The fuel used for these tests was Howell EEE emission test gasoline as requested by Ethyl Corporation. Within the Department of Emissions Research the fuel was coded as EM-1273-F. A copy of the Howell analysis of the fuel is provided in Table 1.

D. Emissions Instrumentation

Heated sample lines before and after the converter test section deliver exhaust sample to the emissions instrument cart. Two complete sets of emission instrumentation are available at the cell for measuring emission concentrations both before and after the catalytic converter being tested. To obtain the converter efficiencies, total HC, CO, NO_x, was measured before and after the converter. In addition, O_2 was measured before and after the converter, and CO_2 before the converter. Total hydrocarbons were measured by heated FID; CO and CO2 by NDIR; O_2 by polarographic instruments; and NOx by heated chemiluminescence. The instruments used are listed in Table 2.

TABLE 2. EMISSIONS INSTRUMENTS

Emission	Instrument	Range
INLET		
HC	Beckman 402 FID	0-2500 ppm
CO	Beckman 315A NDIR	0-15000 ppm
CO_2	Beckman 315B NDIR	0-16%
NO_x	Teco CL	0-2500 ppm
O_2	Beckman OM-11EA	0-5%
OUTLET		
HC	Beckman 402 FID	1000 ppm
CO (low)	Beckman 315B NDIR	0-500 ppm
CO (high)	Beckman 315B NDIR	15000 ppm
NO_x	Teco CL	0-2500 ppm
O_2	Beckman OM-11EA	0-5%

III. CATALYTIC CONVERTERS TESTED

Ethyl Corporation furnished 24 used converters for testing. These converters were from a variety of automobiles. The converters tested were labeled with a single letter plus a single number code. It was our understanding that half of the converters tested had been installed on cars operated on unleaded gasoline, the other half of the converters were from cars using unleaded gasoline with a MMT additive. At the time the converters were tested, we did not know which converters were from cars operated on clear fuel and which converters were from cars operated on fuel with the MMT additive.

Prior to shipment to SwRI, several of their converters had their inlet and exit sections cut off so that the catalyst substrate could be inspected. The inlet and exit cones of these converters were disposed of before it was decided to test them on an engine. To test these converters on the slave engine, it was necessary to obtain used converters of the same design, cut the ends off these converters, and weld the used ends on the Ethyl supplied converters. For four of the converters it was not possible to weld on replacement ends. The substrates were removed from these four converters and fitted into research style converter cans that were on-hand at SwRI. The converters tested are listed in alpha-numeric order in Table 3. The converters that required replacement ends are noted in the table.

IV. TEST PROCEDURES

The performance test on each converter consisted of a light-off test, patterned after the GM "Cell 102 Test," and warmed-up steady state efficiency evaluations at six different redox ratios. Redox ratio is a ratio of reducing components to the oxidizing components in the exhaust. In the literature,(1)* the redox ratio, R, is defined as shown below:

$$R = \frac{CO + H_2 + 3(HC)}{2O_2 + NO}$$

Unfortunately, there was no reliable method available for continuously measuring H_2 in exhaust. It was therefore necessary to estimate the amount of H_2 in the exhaust from the amount of CO in the exhaust. Typically, a multiplier of 1.33 is used for CO.(2) For this study, NO_x was used for NO, so that the redox ratio for this study was defined as:

$$R = \frac{1.33(CO) + 3(HC)}{2O_2 + NO_x}$$

Since we were not set up to calculate this parameter at the test cell, but did have air fuel ratio, at the cell, a curve of redox ratio versus air fuel ratio, developed at the start of testing, was used with A/F ratio to set exhaust condition. The light-off test and steady state efficiency evaluation are described in more detail in the paragraphs below.

A. Light-Off Test

The light-off test begins with the converter below 104°F, and the engine exhaust bypassing the converter. For these tests the engine speed was set at 1800 RPM, the A/F ratio was set at 14.45 and the fuel cycled plus and minus 0.5 A/F ratio about this setting, at a frequency of 1.0 hertz. When a stable engine exhaust temperature of 932°F was reached, the exhaust was switched to flow through the converter, using a quick-acting valve. Emission concentrations were measured continuously before and after the converter and the times to reach 50 percent conversion efficiency for HC, CO and NO_x were calculated.

*Superscript numbers in parentheses refer to References at end of report.

B. Steady-State Performance Test

The warmed-up steady state efficiency evaluations were conducted at the same engine RPM and exhaust temperature as the light-off tests, but at six different redox ratios. These redox ratios were intended to be: 0.25, 0.60, 1.0, 1.3, 1.6, and 1.9. As explained above, A/F ratio was used as the actual parameter changed. The A/F used were 14.85, 14.65, 14.45, 14.40 and 14.30. For the steady-state efficiency tests, sufficient time is allowed for the converter to reach an equilibrium temperature before emissions data are recorded.

C. Test Procedure for Each Converter

As much as possible, all converters from one group (B, E, F, or T) were tested together, but not necessarily in numerical order within the group. Each converter was mounted in the test section, with the exhaust bypassing the converter and flowing through the measuring orifice (see Figure 1.) The converter exhaust flow was then adjusted for the test converter engine size. Since the actual space velocity each converter was originally designed for was not known, the test exhaust flow was determined from the ratio of the test converter engine displacement to the slave engine displacement. This ratio was used with the total slave engine flow to obtain the test converter flow as follows:

$$FLOW_{test} = (DISP_{test}/DISP_{slave}) * FLOW_{slave}$$

After the flow was adjusted to the test value, the fuel control was set for a constant A/F ratio and adjusted to provide the first A/F ratio. The fuel control settings for the plus and minus 1/2 A/F ratios were determined, and set into the fuel control. The fuel control perturbation circuit was switched from "constant" to "one hertz." The quick acting bypass valve was actuated to route the exhaust flow through the converter test section.

For the first few tests, the converter light-off test at 14.45 A/F ratio was run first, then the steady state efficiency evaluations going from lean to rich air fuel ratios (numerically low to high redox ratios.) For the next few tests, the light-off tests were changed to occur in the middle of steady-state A/F tests, just before the steady state 14.45 A/R ratio test was run. It became apparent after a few runs, that the light-off test should be run after all steady-state efficiency evaluations to give the best repeatability and accuracy. The remaining tests were all run with the light-off test following all of the steady-state efficiency evaluations.

The before and after emissions levels were recorded on strip charts. After the completion of the test of each converter, the strip chart data were read and entered into a spreadsheet, and the efficiencies and redox ratio at each A/F ratio calculated. The results from each converter test were faxed to Ethyl as soon as the test data were processed.

D. Test Chronology

Testing was begun on March 1, 1991. A total of 39 complete evaluations (steady-state efficiency plus light-off test) were conducted. Testing was completed on May 13, 1991. The first tests of E1, E2, B13 and B14 were inadvertently run with the fuel control set to 2 hertz rather than one hertz. These converters were retested later in the program with the fuel control at the correct frequency.

E. Quality Assurance Tests

QA tests were run with the Cell 6 QA standard converter before and after the test series. One QA test was run before, and four QA tests were run after the Ethyl test program. Because of the A/F frequency switch had been mislabeled, the QA test prior to the test series was run at two hertz, rather than one hertz. This mislabeling was not discovered until after the first four test converters had been run. This difference in A/F cycling frequency rendered the initial QA converter test unusable in the repeatability calculations.

V. RESULTS

A. Steady-State Efficiency Evaluations

The steady-state efficiency results are shown in Tables 4 to 27. There is one table for each converter, with the tables in alpha-numeric order by converter designation. To aid in comparing the results, the steady-state efficiencies for each emission type are plotted as a function of redox ratio by converter type in Figures 2 to 16. The figures show that while there are differences in converter efficiencies from one converter design to another, within a given design, all the efficiencies fall within a narrow band.

B. Light-Off Tests

The light-off times are given at the bottom of the steady-state test results in Tables 4 to 27. They are shown in histograms, with all converters of the same type on the same graph in Figures 17 to 21. Because of the nature of the test, there is a larger variation in the light-off times than in the steady-state efficiencies.

C. Quality Assurance

For the same engine A/F ratio, there were variations in emissions concentrations at the converter inlet, and consequently some variation in redox ratio from test-to-test. The inlet concentrations for each emission type for all tests are listed in the Appendix B. The exhaust temperature at the converter inlet was held constant by means of fans on the exhaust piping, thus the temperature of the exhaust upstream of the converter varied somewhat while the converter inlet temperature stayed constant. It is hypothesized that the variations in converter inlet concentration were due the different reaction rates in the exhaust system caused by small variations in the exhaust system temperatures. These different concentrations then caused slightly different redox ratios for the same A/F ratio.

To determine the concentration changes in the exhaust system, emission measurements were made in the exhaust ports and in the converter inlet at different A/F ratios and at two different temperatures. The results of those tests are shown in Table 28. For the 930°F measurements, note that the HC, CO, and O_2 concentrations are less, while the NO_x, CO_2 are greater than the exhaust port concentrations, indicating that the HC and CO had been oxidized in the exhaust system and that some NO_x had been formed. At the lower temperature of 750°F, the HC and CO were also oxidized in the exhaust system, but no NO_x was formed. Also note the difference in the value of the redox ratio between the exhaust port and the catalyst inlet for the same A/F ratio. Graphs of the A/F ratio as a function of redox ratio for each converter by converter type are located in Appendix B.

Repeatability was defined by tests of the QA converter. Prior to running the post-project QA tests, some scheduled update of the test cell instrumentation was permitted to begin. This work consisted of connecting the emissions instruments to a computer controlled data logging system. There should have been no effect on the emissions measurement system. However, it was discovered in later analysis of the QA tests that because of an error in wiring, the converter inlet recorder HC and NO_X channels had been damaged so that they did not respond in a linear manner. Thus, only the CO data from the QA checks are valid. These data are presented in graphic form in Figure 22. Because the A/F ratios give slightly different redox ratios, the CO efficiency was plotted as a function of redox ratio, and a curve fit determined for each set of test data. The range of CO efficiency at several redox ratios was then determined from the curves. These efficiency ranges are shown below.

TABLE 29. CO EFFICIENCY SPREAD FOR QA CONVERTER TESTS

Redox Ratio	CO % Efficiency Spread
0.6	0.2
0.8	0.2
0.1	<3.5
1.2	3.5
1.4	3.5
1.6	3.0
1.8	3.0
2.0	4.0

The efficiency spread can be used as an indication of the test-to-test and day-to-day repeatability.

REFERENCES

1. Hammerle, R.H., and Wu, C.H., "Three-Way Catalyst Performance Characterization" SAE Paper 810275.

TABLES

TABLE 1. ANALYSIS OF EM-1273-F UNLEADED GASOLINE

HOWELL HYDROCARBONS INC.
EEE UNLEADED GASOLINE

BATCH NO: 90S-17 TANK NO: 215 DATE APPROVED: OCTOBER 27, 1990

TEST	ASTM	HHI SPECS. MIN.	HHI SPECS. MAX.	FED SPECS. MIN.	FED SPECS. MAX.	ANALYTICAL RESULTS HHI	ANALYTICAL RESULTS G.H.
Specific gravity, 60/60	D1298	0.734	0.744			0.744	0.742
Gravity, °API	D1298	58.7	61.2			58.8	59.07
Research octane number	D2699	96.0		93.0		96.0	
Motor octane number	D2700	Report				88.0	
Sensitivity		7.5		7.5		8.0	
Lead, gm/gal	D3237	0.000	0.050	0.00	0.05	0.000	0.002
Distillation, °F	D86						
IBP		75	95	75	95	90	93
10%		120	135	120	135	129	128
50%		200	230	200	230	222	220
90%		300	325	300	325	313	308
EP			415		415	391	376
Sulfur, wt%	D3120		0.100		0.10	0.002	0.005
Phosphorous, gm/gal	D3231		0.005		0.005	NIL	0.0001
Reid vapor pressure, psi	D323	8.8	9.2	8.7	9.2	9.1	9.0
Hydrocarbon composition, vol%	D1319						
Aromatics			35.0		35.0	32.7	30.2
Olefins			10.0		10.0	2.5	2.6
Saturates		Report				65.8	67.6
Existent gum, mg/100ml	D381		5.0		(a)	1.2	1.76
Copper strip corrosion	D130		1		(a)	1A	
Oxidation stability	D525	240			(a)	240+	
Particulate matter, mg/l	D2276		1.0		(a)	0.2	
*Fuel economy numerator		2601	2661		(a)	2639	
*C Factor		Report			(a)	0.9967	
Alcohol, vol%			0		(a)	0	
Carbon weight fraction	E191	Report			(a)	0.8621	
Hydrogen weight fraction	E191	Report			(a)	0.1321	
Net heating value, btu/lb	D240	Report			(a)	18566	18510
Carbon weight fraction	D3343	Report			(a)	0.8673	0.866
Net heating value, btu/lb	D3338	Report			(a)	18618	18660
Color						GREEN	

APPROVED BY:

*Fuel economy numerator & C factor calculated using E-191 & D-240 values.
**To be reported at a later date.

(a) No requirements or not addressed.

TABLE 2. EMISSIONS INSTRUMENTS

Emission	Instrument	Range
INLET		
HC	Beckman 402 FID	0-2500 ppm
CO	Beckman 315A NDIR	0-15000 ppm
CO_2	Beckman 315B NDIR	0-16%
NO_x	Teco CL	0-2500 ppm
O_2	Beckman OM-11EA	0-5%
OUTLET		
HC	Beckman 402 FID	1000 ppm
CO (low)	Beckman 315B NDIR	0-500 ppm
CO (high)	Beckman 315B NDIR	15000 ppm
NO_x	Teco CL	0-2500 ppm
O_2	Beckman OM-11EA	0-5%

TABLE 3. LIST OF CONVERTERS TESTED

Converter Designation	Vehicle Engine Size, Liters	Test Dates
B-7	2.8	4/12, 5/6
B-8	2.8	4/16, 5/9
B-9	2.8	4/17
B-10	2.8	4/16, 5/6
B-11*	2.8	4/17
B-12*	2.8	4/16, 5/13
B-13*	3.8	3/11, 3/25, 3/29
B-14*	3.8	3/8, 3/26, 3/29
E-1*	1.9	3/1, 3/21, 3/28, 4/23
E-2*	1.9	3/4, 3/22, 3/26, 3/28
E-3	1.9	4/10
E-4	1.9	4/10
E-5	1.9	4/11
E-6	1.9	4/11
F2LA**	5.0 (1 bank)	4/29
F2RA**	5.0 (1 bank)	4/24
F6RA**	5.0 (1 bank)	4/24
F6LA**	5.0 (1 bank)	4/25
T-1	3.0	4/1
T-2	3.0	4/1
T-3	3.0	4/3
T-4	3.0	4/3
T-5*	3.0	4/4
T-6*	3.0	4/4

Notes:
* These converters had replacement ends welded on cans.
** These catalyst bricks were put in research type cans.

TABLE 4. TEST RESULTS FOR CONVERTER B-7

TEST NO.	TARGET/ CALCULATED AIR-FUEL RATIO	EXHAUST CONSTITUENTS AND UNITS	CATALYST INLET CONCENTRATION	50% CONVERSION LIGHT-OFF TIME, (SEC)	EFFICIENCY, %	REDOX RATIO
B-7	14.85	HC, ppmC	100		82.3	0.208
5/6/91	14.95	LOW CO, ppm	0		98.7	
		CO, ppm	2380		99.5	
		NOX, ppm	1622		28.1	
		CO2, %	14.33			
		O2, %	0.75			
	14.65	HC, ppmC	224		93.1	0.576
	14.67	LOW CO, ppm	0		99.4	
		CO, ppm	4519		99.7	
		NOX, ppm	1588		63.1	
		CO2, %	14.33			
		O2, %	0.50			
	14.55	HC, ppmC	262		93.7	0.769
	14.59	LOW CO, ppm	0		99.4	
		CO, ppm	5522		99.6	
		NOX, ppm	1566		78.4	
		CO2, %	14.49			
		O2, %	0.45			
	14.45	HC, ppmC	374		89.2	1.347
	14.42	LOW CO, ppm	0		76.1	
		CO, ppm	7780		78.3	
		NOX, ppm	1510		92.5	
		CO2, %	14.49			
		O2, %	0.35			
	14.4	HC, ppmC	386		86.4	1.437
	14.40	LOW CO, ppm	0		66.4	
		CO, ppm	8093		69.3	
		NOX, ppm	1488		89.9	
		CO2, %	14.33			
		O2, %	0.34			
	14.30	HC, ppmC	424		82.1	1.790
	14.33	LOW CO, ppm	0		—	
		CO, ppm	9128		45.6	
		NOX, ppm	1488		87.3	
		CO2, %	14.33			
		O2, %	0.30			
	14.45	HC, ppmC	349	12.5	84.4	1.235
		LOW CO, ppm	0	—	62.7	
		CO, ppm	7163	27.5	64.4	
		NOX, ppm	1555	13.0	91.1	
		CO2, %	14.33			
		O2, %	0.35			

TABLE 5. TEST RESULTS FOR CONVERTER B-8

TEST NO.	TARGET/ CALCULATED AIR-FUEL RATIO	EXHAUST CONSTITUENTS AND UNITS	CATALYST INLET CONCENTRATION	50% CONVERSION LIGHT-OFF TIME, (SEC)	EFFICIENCY, %	REDOX RATIO
B-8	14.85	HC, ppmC	87		86.0	0.213
5/09/91	14.91	LOW CO, ppm	0		99.3	
		CO, ppm	2177		98.9	
		NOX, ppm	1310		19.4	
		CO2, %	14.65			
		O2, %	0.68			
	14.65	HC, ppmC	212		94.2	0.637
	14.64	LOW CO, ppm	0		99.6	
		CO, ppm	4448		99.5	
		NOX, ppm	1277		67.7	
		CO2, %	14.65			
		O2, %	0.45			
	14.55	HC, ppmC	249		96.1	0.887
	14.56	LOW CO, ppm	0		99.6	
		CO, ppm	5232		99.5	
		NOX, ppm	1186		83.0	
		CO2, %	14.65			
		O2, %	0.38			
	14.45	HC, ppmC	361		91.2	1.301
	14.45	LOW CO, ppm	0		84.4	
		CO, ppm	6707		81.5	
		NOX, ppm	1186		90.4	
		CO2, %	14.65			
		O2, %	0.33			
	14.4	HC, ppmC	411		88.1	1.558
	14.40	LOW CO, ppm	0		74.3	
		CO, ppm	7470		65.9	
		NOX, ppm	1163		88.1	
		CO2, %	14.49			
		O2, %	0.30			
	14.30	HC, ppmC	449		80.9	2.186
	14.30	LOW CO, ppm	0		—	
		CO, ppm	9047		37.9	
		NOX, ppm	1117		85.4	
		CO2, %	14.49			
		O2, %	0.25			
	14.45	HC, ppmC	374	12.5	92.1	1.304
		LOW CO, ppm	0	—	89.3	
		CO, ppm	6707	22.5	88.1	
		NOX, ppm	1197	16.0	93.7	
		CO2, %	14.49			
		O2, %	0.33			

TABLE 6. TEST RESULTS FOR CONVERTER B-9

TEST NO.	TARGET/ CALCULATED AIR-FUEL RATIO	EXHAUST CONSTITUENTS AND UNITS	CATALYST INLET CONCENTRATION	50% CONVERSION LIGHT-OFF TIME, (SEC)	EFFICIENCY, %	REDOX RATIO
B-9	14.85	HC, ppmC	70		76.3	0.208
4/17/91	14.89	LOW CO, ppm	0		99.4	
		CO, ppm	2109		99.4	
		NOX, ppm	1366		23.6	
		CO2, %	14.81			
		O2, %	0.66			
	14.65	HC, ppmC	174		90.5	0.615
	14.65	LOW CO, ppm	0		99.4	
		CO, ppm	4307		99.4	
		NOX, ppm	1277		59.0	
		CO2, %	14.81			
		O2, %	0.44			
	14.55	HC, ppmC	212		91.2	0.763
	14.59	LOW CO, ppm	0		99.6	
		CO, ppm	4845		99.7	
		NOX, ppm	1272		68.5	
		CO2, %	14.81			
		O2, %	0.40			
	14.45	HC, ppmC	287		90.4	1.217
	14.47	LOW CO, ppm	0		94.8	
		CO, ppm	6377		94.6	
		NOX, ppm	1254		94.0	
		CO2, %	14.81			
		O2, %	0.32			
	14.4	HC, ppmC	312		88.7	1.464
	14.42	LOW CO, ppm	0		86.4	
		CO, ppm	7086		85.9	
		NOX, ppm	1245		92.9	
		CO2, %	14.84			
		O2, %	0.29			
	14.30	HC, ppmC	396		84.1	2.121
	14.31	LOW CO, ppm	0		--	
		CO, ppm	8727		54.6	
		NOX, ppm	1186		91.5	
		CO2, %	14.81			
		O2, %	0.24			
	14.45	HC, ppmC	299	9.5	89.0	1.430
		LOW CO, ppm	0	—	89.3	
		CO, ppm	6707	18.0	89.8	
		NOX, ppm	1231	18.5	96.5	
		CO2, %	14.91			
		O2, %	0.28			

TABLE 7. TEST RESULTS FOR CONVERTER B-10

TEST NO.	TARGET/ CALCULATED AIR-FUEL RATIO	EXHAUST CONSTITUENTS AND UNITS	CATALYST INLET CONCENTRATION	50% CONVERSION LIGHT-OFF TIME, (SEC)	EFFICIENCY, %	REDOX RATIO
B-10	14.85	HC, ppmC	82		73.2	0.213
5/6/91	14.91	LOW CO, ppm	0		99.3	
		CO, ppm	2217		99.5	
		NOX, ppm	1521		19.2	
		CO2, %	14.49			
		O2, %	0.68			
	14.65	HC, ppmC	162		86.4	0.467
	14.71	LOW CO, ppm	0		99.5	
		CO, ppm	3680		99.7	
		NOX, ppm	1510		49.8	
		CO2, %	14.65			
		O2, %	0.50			
	14.55	HC, ppmC	237		91.6	0.719
	14.61	LOW CO, ppm	0		99.5	
		CO, ppm	4874		99.8	
		NOX, ppm	1499		69.2	
		CO2, %	14.55			
		O2, %	0.43			
	14.45	HC, ppmC	287		93.8	1.049
	14.50	LOW CO, ppm	0		98.0	
		CO, ppm	6213		97.7	
		NOX, ppm	1488		94.1	
		CO2, %	14.49			
		O2, %	0.36			
	14.4	HC, ppmC	349		90.6	1.411
	14.41	LOW CO, ppm	0		86.4	
		CO, ppm	7470		86.0	
		NOX, ppm	1477		93.2	
		CO2, %	14.49			
		O2, %	0.32			
	14.30	HC, ppmC	411		86.7	1.891
	14.32	LOW CO, ppm	0		66.4	
		CO, ppm	8967		66.3	
		NOX, ppm	1455		90.8	
		CO2, %	14.33			
		O2, %	0.28			
	14.45	HC, ppmC	262	10.0	92.4	0.984
		LOW CO, ppm	0	12.0	99.1	
		CO, ppm	6109	12.5	99.0	
		NOX, ppm	1543	12.5	87.0	
		CO2, %	14.49			
		O2, %	0.38			

TABLE 8. TEST RESULTS FOR CONVERTER B-11

TEST NO.	TARGET/ CALCULATED AIR–FUEL RATIO	EXHAUST CONSTITUENTS AND UNITS	CATALYST INLET CONCENTRATION	50% CONVERSION LIGHT–OFF TIME, (SEC)	EFFICIENCY, %	REDOX RATIO
B–11	14.85	HC, ppmC	57		88.4	0.205
4/17/91	14.90	LOW CO, ppm	0		99.2	
		CO, ppm	2041		91.0	
		NOX, ppm	1247		20.4	
		CO2, %	14.33			
		O2, %	0.64			
	14.65	HC, ppmC	150		92.6	0.556
	14.67	LOW CO, ppm	0		99.6	
		CO, ppm	3888		94.6	
		NOX, ppm	1220		56.0	
		CO2, %	14.49			
		O2, %	0.44			
	14.55	HC, ppmC	224		92.6	0.894
	14.55	LOW CO, ppm	0		99.1	
		CO, ppm	5305		95.6	
		NOX, ppm	1231		74.0	
		CO2, %	14.49			
		O2, %	0.37			
	14.45	HC, ppmC	249		91.6	1.193
	14.48	LOW CO, ppm	0		98.4	
		CO, ppm	5888		95.8	
		NOX, ppm	1163		92.4	
		CO2, %	14.39			
		O2, %	0.30			
	14.4	HC, ppmC	287		89.3	1.462
	14.43	LOW CO, ppm	0		92.8	
		CO, ppm	6556		89.2	
		NOX, ppm	1117		94.4	
		CO2, %	14.39			
		O2, %	0.27			
	14.30	HC, ppmC	374		82.6	2.396
	14.29	LOW CO, ppm	0		—	
		CO, ppm	8567		48.8	
		NOX, ppm	1070		89.4	
		CO2, %	14.42			
		O2, %	0.21			
	14.45	HC, ppmC	254	13.0	92.6	1.116
		LOW CO, ppm	0	19.5	97.6	
		CO, ppm	5668	20.0	93.9	
		NOX, ppm	1209	16.5	93.7	
		CO2, %	14.49			
		O2, %	0.31			

TABLE 9. TEST RESULTS FOR CONVERTER B-12

TEST NO.	TARGET/ CALCULATED AIR-FUEL RATIO	EXHAUST CONSTITUENTS AND UNITS	CATALYST INLET CONCENTRATION	50% CONVERSION LIGHT-OFF TIME, (SEC)	EFFICIENCY, %	REDOX RATIO
B-12	14.85	HC, ppmC	87		84.3	0.214
5/13/91	14.91	LOW CO, ppm	0		99.1	
		CO, ppm	2177		98.9	
		NOX, ppm	1254		36.6	
		CO2, %	14.65			
		O2, %	0.68			
	14.65	HC, ppmC	174		90.7	0.546
	14.67	LOW CO, ppm	0		98.9	
		CO, ppm	3818		98.7	
		NOX, ppm	1254		60.2	
		CO2, %	14.65			
		O2, %	0.45			
	14.55	HC, ppmC	287		94.0	0.835
	14.57	LOW CO, ppm	0		98.8	
		CO, ppm	5160		98.4	
		NOX, ppm	1243		83.8	
		CO2, %	14.81			
		O2, %	0.40			
	14.45	HC, ppmC	312		90.6	1.162
	14.48	LOW CO, ppm	0		88.1	
		CO, ppm	6035		88.9	
		NOX, ppm	1209		93.7	
		CO2, %	14.81			
		O2, %	0.33			
	14.4	HC, ppmC	374		86.9	1.478
	14.42	LOW CO, ppm	0		66.7	
		CO, ppm	7163		67.2	
		NOX, ppm	1197		90.5	
		CO2, %	14.81			
		O2, %	0.30			
	14.30	HC, ppmC	424		81.5	1.874
	14.34	LOW CO, ppm	0		—	
		CO, ppm	8488		38.9	
		NOX, ppm	1197		85.3	
		CO2, %	14.65			
		O2, %	0.28			
	14.45	HC, ppmC	324	11.0	93.2	1.009
		LOW CO, ppm	0	20.0	97.1	
		CO, ppm	5888	19.0	95.9	
		NOX, ppm	1220	12.0	94.8	
		CO2, %	14.65			
		O2, %	0.38			

TABLE 10. TEST RESULTS FOR CONVERTER B-13

TEST NO.	TARGET/ CALCULATED AIR-FUEL RATIO	EXHAUST CONSTITUENTS AND UNITS	CATALYST INLET CONCENTRATION	50% CONVERSION LIGHT-OFF TIME, (SEC)	EFFICIENCY, %	REDOX RATIO
B-13	14.85	HC, ppmC	120		87.1	0.188
3/29/91	14.94	LOW CO, ppm	0		99.4	
		CO, ppm	1906		--	
		NOX, ppm	1577		29.9	
		CO2, %	14.17			
		O2, %	0.69			
	14.65	HC, ppmC	174		92.4	0.613
	14.66	LOW CO, ppm	0		99.8	
		CO, ppm	4945		--	
		NOX, ppm	1521		56.9	
		CO2, %	14.17			
		O2, %	0.50			
	14.55	HC, ppmC	214		93.8	0.713
	14.62	LOW CO, ppm	0		99.6	
		CO, ppm	5449		--	
		NOX, ppm	1488		63.1	
		CO2, %	14.33			
		O2, %	0.48			
	14.45	HC, ppmC	274		96.0	1.042
	14.50	LOW CO, ppm	0		98.2	
		CO, ppm	6707		--	
		NOX, ppm	1443		92.0	
		CO2, %	14.02			
		O2, %	0.40			
	14.4	HC, ppmC	324		91.9	1.320
	14.43	LOW CO, ppm	0		90.6	
		CO, ppm	7547		--	
		NOX, ppm	1421		92.0	
		CO2, %	14.33			
		O2, %	0.35			
	14.30	HC, ppmC	374		86.0	1.771
	14.34	LOW CO, ppm	0		71.6	
		CO, ppm	8887		--	
		NOX, ppm	1377		87.2	
		CO2, %	14.17			
		O2, %	0.30			
	14.45	HC, ppmC	287	12.5	96.1	1.152
		LOW CO, ppm	0	13.5	98.2	
		CO, ppm	7010	--	--	
		NOX, ppm	1432	14.5	91.9	
		CO2, %	14.02			
		O2, %	0.37			

TABLE 11. TEST RESULTS FOR CONVERTER B-14

TEST NO.	TARGET/ CALCULATED AIR-FUEL RATIO	EXHAUST CONSTITUENTS AND UNITS	CATALYST INLET CONCENTRATION	50% CONVERSION LIGHT-OFF TIME, (SEC)	EFFICIENCY, %	REDOX RATIO
B-14	14.85	HC, ppmC	130		88.9	0.282
3/29/91	14.88	LOW CO, ppm	0		99.5	
		CO, ppm	2992		--	
		NOX, ppm	1668		30.8	
		CO2, %	14.49			
		O2, %	0.69			
	14.65	HC, ppmC	192		93.1	0.525
	14.70	LOW CO, ppm	0		99.6	
		CO, ppm	4307		--	
		NOX, ppm	1634		51.3	
		CO2, %	14.49			
		O2, %	0.52			
	14.55	HC, ppmC	239		95.8	0.742
	14.60	LOW CO, ppm	0		99.7	
		CO, ppm	5305		--	
		NOX, ppm	1588		66.2	
		CO2, %	14.49			
		O2, %	0.44			
	14.45	HC, ppmC	312		91.9	1.224
	14.45	LOW CO, ppm	0		90.0	
		CO, ppm	7086		--	
		NOX, ppm	1548		91.1	
		CO2, %	14.33			
		O2, %	0.35			
	14.4	HC, ppmC	349		90.6	1.430
	14.40	LOW CO, ppm	0		83.9	
		CO, ppm	7780		--	
		NOX, ppm	1543		87.0	
		CO2, %	14.49			
		O2, %	0.32			
	14.30	HC, ppmC	374		85.4	1.651
	14.36	LOW CO, ppm	0		--	
		CO, ppm	8408		64.5	
		NOX, ppm	1521		86.8	
		CO2, %	14.49			
		O2, %	0.30			
	14.45	HC, ppmC	349	11.0	93.7	1.137
		LOW CO, ppm	0	24.5	91.5	
		CO, ppm	7316	--	--	
		NOX, ppm	1577	13.0	92.8	
		CO2, %	14.33			
		O2, %	0.40			

TABLE 12. TEST RESULTS FOR CONVERTER E-1

TEST NO.	TARGET/ CALCULATED AIR-FUEL RATIO	EXHAUST CONSTITUENTS AND UNITS	CATALYST INLET CONCENTRATION	50% CONVERSION LIGHT-OFF TIME, (SEC)	EFFICIENCY, %	REDOX RATIO
E-1	14.85	HC, ppmC	75		70.6	0.230
4/23/91	14.85	LOW CO, ppm	0		95.0	
		CO, ppm	2109		94.3	
		NOX, ppm	1321		31.4	
		CO2, %	14.97			
		O2, %	0.59			
	14.65	HC, ppmC	137		76.0	0.522
	14.68	LOW CO, ppm	0		89.0	
		CO, ppm	3680		90.1	
		NOX, ppm	1277		57.0	
		CO2, %	14.81			
		O2, %	0.44			
	14.55	HC, ppmC	199		75.4	0.950
	14.54	LOW CO, ppm	0		76.9	
		CO, ppm	5017		77.8	
		NOX, ppm	1231		67.5	
		CO2, %	14.81			
		O2, %	0.32			
	14.45	HC, ppmC	274		74.3	1.374
	14.44	LOW CO, ppm	0		56.6	
		CO, ppm	6258		58.2	
		NOX, ppm	1220		75.4	
		CO2, %	14.65			
		O2, %	0.27			
	14.4	HC, ppmC	312		75.6	1.936
	14.36	LOW CO, ppm	0		—	
		CO, ppm	7470		45.8	
		NOX, ppm	1163		82.7	
		CO2, %	14.65			
		O2, %	0.22			
	14.30	HC, ppmC	336		72.7	2.069
	14.34	LOW CO, ppm	0		—	
		CO, ppm	7936		35.6	
		NOX, ppm	1140		83.5	
		CO2, %	14.65			
		O2, %	0.22			
	14.45	HC, ppmC	249	25.0	71.7	1.386
		LOW CO, ppm	0	66.5	55.1	
		CO, ppm	6258	65.0	56.1	
		NOX, ppm	1105	21.0	73.9	
		CO2, %	14.81			
		O2, %	0.27			

TABLE 13. TEST RESULTS FOR CONVERTER E-2

TEST NO.	TARGET/ CALCULATED AIR-FUEL RATIO	EXHAUST CONSTITUENTS AND UNITS	CATALYST INLET CONCENTRATION	50% CONVERSION LIGHT-OFF TIME, (SEC)	EFFICIENCY, %	REDOX RATIO
E-2	14.85	HC, ppmC	100		75.7	0.303
3/28/91	14.84	LOW CO, ppm	0		95.7	
		CO, ppm	2856		—	
		NOX, ppm	1186		36.0	
		CO2, %	14.49			
		O2, %	0.62			
	14.65	HC, ppmC	174		76.2	0.584
	14.67	LOW CO, ppm	0		76.8	
		CO, ppm	4237		—	
		NOX, ppm	1163		51.8	
		CO2, %	14.49			
		O2, %	0.47			
	14.55	HC, ppmC	249		76.0	0.902
	14.56	LOW CO, ppm	0		60.0	
		CO, ppm	5522		—	
		NOX, ppm	1070		59.1	
		CO2, %	14.17			
		O2, %	0.40			
	14.45	HC, ppmC	299		74.6	1.233
	14.47	LOW CO, ppm	0		52.2	
		CO, ppm	6707		—	
		NOX, ppm	1046		64.1	
		CO2, %	14.02			
		O2, %	0.35			
	14.4	HC, ppmC	324		74.9	1.403
	14.43	LOW CO, ppm	0		—	
		CO, ppm	7163		38.8	
		NOX, ppm	1058		66.9	
		CO2, %	14.17			
		O2, %	0.32			
	14.30	HC, ppmC	399		71.5	1.893
	14.33	LOW CO, ppm	0		—	
		CO, ppm	9047		31.3	
		NOX, ppm	1058		73.9	
		CO2, %	14.17			
		O2, %	0.30			
	14.45	HC, ppmC	299	34.5	76.4	1.206
		LOW CO, ppm	0	29.5	55.5	
		CO, ppm	6556	—	—	
		NOX, ppm	1058	29.0	63.4	
		CO2, %	14.17			
		O2, %	0.35			

TABLE 14. TEST RESULTS FOR CONVERTER E-3

TEST NO.	TARGET/ CALCULATED AIR-FUEL RATIO	EXHAUST CONSTITUENTS AND UNITS	CATALYST INLET CONCENTRATION	50% CONVERSION LIGHT-OFF TIME, (SEC)	EFFICIENCY, %	REDOX RATIO
E-3	14.85	HC, ppmC	55		63.8	0.261
4/10/91	14.83	LOW CO, ppm	0		99.2	
		CO, ppm	2448		97.5	
		NOX, ppm	1443		22.6	
		CO2, %	14.65			
		O2, %	0.58			
	14.65	HC, ppmC	125		75.3	0.643
	14.63	LOW CO, ppm	0		94.0	
		CO, ppm	4378		93.8	
		NOX, ppm	1432		57.4	
		CO2, %	14.49			
		O2, %	0.41			
	14.55	HC, ppmC	174		78.0	0.959
	14.53	LOW CO, ppm	0		84.1	
		CO, ppm	5232		83.3	
		NOX, ppm	1377		64.6	
		CO2, %	14.65			
		O2, %	0.32			
	14.45	HC, ppmC	212		79.4	1.128
	14.49	LOW CO, ppm	0		80.0	
		CO, ppm	6035		79.6	
		NOX, ppm	1355		66.8	
		CO2, %	14.49			
		O2, %	0.32			
	14.4	HC, ppmC	274		78.2	1.756
	14.37	LOW CO, ppm	0		—	
		CO, ppm	7625		55.4	
		NOX, ppm	1299		78.8	
		CO2, %	14.49			
		O2, %	0.25			
	14.30	HC, ppmC	312		79.1	1.859
	14.34	LOW CO, ppm	0		—	
		CO, ppm	8408		53.9	
		NOX, ppm	1277		78.4	
		CO2, %	14.33			
		O2, %	0.26			
	14.45	HC, ppmC	254	23.8	79.4	1.587
		LOW CO, ppm	0	—	67.1	
		CO, ppm	7010	42.0	64.2	
		NOX, ppm	1410	22.0	72.5	
		CO2, %	14.33			
		O2, %	0.25			

TABLE 15. TEST RESULTS FOR CONVERTER E-4

TEST NO.	TARGET/ CALCULATED AIR-FUEL RATIO	EXHAUST CONSTITUENTS AND UNITS	CATALYST INLET CONCENTRATION	50% CONVERSION LIGHT-OFF TIME, (SEC)	EFFICIENCY, %	REDOX RATIO
E-4	14.85	HC, ppmC	40		75.1	0.186
4/10/91	14.92	LOW CO, ppm	0		98.2	
		CO, ppm	1974		95.7	
		NOX, ppm	1399		18.4	
		CO2, %	14.42			
		O2, %	0.67			
	14.65	HC, ppmC	125		82.3	0.621
	14.63	LOW CO, ppm	0		93.8	
		CO, ppm	4027		93.9	
		NOX, ppm	1321		54.7	
		CO2, %	14.49			
		O2, %	0.40			
	14.55	HC, ppmC	174		84.3	0.865
	14.56	LOW CO, ppm	0		89.5	
		CO, ppm	4945		89.3	
		NOX, ppm	1288		63.2	
		CO2, %	14.49			
		O2, %	0.35			
	14.45	HC, ppmC	212		79.4	1.366
	14.45	LOW CO, ppm	0		72.0	
		CO, ppm	6183		70.2	
		NOX, ppm	1243		70.8	
		CO2, %	14.49			
		O2, %	0.26			
	14.4	HC, ppmC	249		81.1	1.634
	14.40	LOW CO, ppm	0		61.9	
		CO, ppm	6782		63.0	
		NOX, ppm	1231		75.6	
		CO2, %	14.49			
		O2, %	0.24			
	14.30	HC, ppmC	324		79.9	2.410
	14.29	LOW CO, ppm	0		--	
		CO, ppm	8567		48.8	
		NOX, ppm	1174		83.5	
		CO2, %	14.33			
		O2, %	0.20			
	14.45	HC, ppmC	212	20.5	79.4	1.443
		LOW CO, ppm	0	22.5	67.4	
		CO, ppm	6258	23.5	64.2	
		NOX, ppm	1265	25.5	68.4	
		CO2, %	14.33			
		O2, %	0.25			

TABLE 16. TEST RESULTS FOR CONVERTER E-5

TEST NO.	TARGET/ CALCULATED AIR-FUEL RATIO	EXHAUST CONSTITUENTS AND UNITS	CATALYST INLET CONCENTRATION	50% CONVERSION LIGHT-OFF TIME, (SEC)	EFFICIENCY, %	REDOX RATIO
E-5	14.85	HC, ppmC	37		64.6	0.233
4/11/91	14.86	LOW CO, ppm	0		--	
		CO, ppm	2177		96.6	
		NOX, ppm	1070		18.7	
		CO2, %	14.33			
		O2, %	0.59			
	14.65	HC, ppmC	75		70.6	0.479
	14.68	LOW CO, ppm	0		--	
		CO, ppm	3061		95.6	
		NOX, ppm	1058		49.3	
		CO2, %	14.65			
		O2, %	0.40			
	14.55	HC, ppmC	174		78.0	1.039
	14.52	LOW CO, ppm	0		--	
		CO, ppm	5204		72.2	
		NOX, ppm	1034		62.5	
		CO2, %	14.49			
		O2, %	0.31			
	14.45	HC, ppmC	199		78.1	1.429
	14.45	LOW CO, ppm	0		--	
		CO, ppm	5961		65.8	
		NOX, ppm	1022		73.0	
		CO2, %	14.49			
		O2, %	0.25			
	14.4	HC, ppmC	224		75.7	1.698
	14.41	LOW CO, ppm	0		--	
		CO, ppm	6481		57.1	
		NOX, ppm	1022		74.2	
		CO2, %	14.49			
		O2, %	0.22			
	14.30	HC, ppmC	312		77.4	2.740
	14.28	LOW CO, ppm	0		--	
		CO, ppm	8488		36.4	
		NOX, ppm	998		83.6	
		CO2, %	14.49			
		O2, %	0.17			
	14.45	HC, ppmC	187	21.5	76.6	1.200
		LOW CO, ppm	0	--	--	
		CO, ppm	5449	40.5	61.3	
		NOX, ppm	1070	25.5	62.6	
		CO2, %	14.33			
		O2, %	0.27			

TABLE 17. TEST RESULTS FOR CONVERTER E-6

TEST NO.	TARGET/ CALCULATED AIR-FUEL RATIO	EXHAUST CONSTITUENTS AND UNITS	CATALYST INLET CONCENTRATION	50% CONVERSION LIGHT-OFF TIME, (SEC)	EFFICIENCY, %	REDOX RATIO
E-6	14.85	HC, ppmC	37		70.5	0.223
4/11/91	14.87	LOW CO, ppm	0		98.6	
		CO, ppm	2177		88.7	
		NOX, ppm	1174		17.5	
		CO2, %	14.49			
		O2, %	0.62			
	14.65	HC, ppmC	100		77.9	0.499
	14.69	LOW CO, ppm	0		93.7	
		CO, ppm	3542		87.8	
		NOX, ppm	1151		48.1	
		CO2, %	14.65			
		O2, %	0.44			
	14.55	HC, ppmC	162		79.7	0.830
	14.57	LOW CO, ppm	0		88.4	
		CO, ppm	4660		84.0	
		NOX, ppm	1140		56.2	
		CO2, %	14.65			
		O2, %	0.35			
	14.45	HC, ppmC	212		76.8	1.193
	14.48	LOW CO, ppm	0		66.0	
		CO, ppm	5814		59.9	
		NOX, ppm	1082		64.2	
		CO2, %	14.49			
		O2, %	0.30			
	14.4	HC, ppmC	224		75.7	1.506
	14.43	LOW CO, ppm	0		63.5	
		CO, ppm	6332		58.2	
		NOX, ppm	1093		67.9	
		CO2, %	14.49			
		O2, %	0.25			
	14.30	HC, ppmC	324		76.6	2.750
	14.28	LOW CO, ppm	0		—	
		CO, ppm	8567		33.5	
		NOX, ppm	1034		79.4	
		CO2, %	14.49			
		O2, %	0.17			
	14.45	HC, ppmC	199	18.5	78.1	1.110
		LOW CO, ppm	0	15.0	68.0	
		CO, ppm	5814	17.0	62.6	
		NOX, ppm	1082	30.5	60.7	
		CO2, %	14.49			
		O2, %	0.32			

TABLE 18. TEST RESULTS FOR CONVERTER F2LA

TEST NO.	TARGET/ CALCULATED AIR-FUEL RATIO	EXHAUST CONSTITUENTS AND UNITS	CATALYST INLET CONCENTRATION	50% CONVERSION LIGHT-OFF TIME, (SEC)	EFFICIENCY, %	REDOX RATIO
F2LA	14.85	HC, ppmC	87		74.8	0.251
4/29/91	14.84	LOW CO, ppm	0		95.3	
		CO, ppm	2353		95.9	
		NOX, ppm	1668		22.6	
		CO2, %	14.49			
		O2, %	0.59			
	14.65	HC, ppmC	174		81.1	0.569
	14.66	LOW CO, ppm	0		89.5	
		CO, ppm	4097		89.6	
		NOX, ppm	1611		52.9	
		CO2, %	14.49			
		O2, %	0.44			
	14.55	HC, ppmC	224		80.5	0.747
	14.59	LOW CO, ppm	0		81.1	
		CO, ppm	4945		81.3	
		NOX, ppm	1611		57.5	
		CO2, %	14.49			
		O2, %	0.41			
	14.45	HC, ppmC	287		79.1	1.151
	14.47	LOW CO, ppm	0		63.1	
		CO, ppm	6258		62.5	
		NOX, ppm	1555		65.5	
		CO2, %	14.49			
		O2, %	0.32			
	14.4	HC, ppmC	324		76.6	1.562
	14.39	LOW CO, ppm	0		56.7	
		CO, ppm	7470		55.9	
		NOX, ppm	1543		72.5	
		CO2, %	14.49			
		O2, %	0.27			
	14.30	HC, ppmC	374		76.9	2.078
	14.31	LOW CO, ppm	0		—	
		CO, ppm	8488		43.1	
		NOX, ppm	1521		79.4	
		CO2, %	14.49			
		O2, %	0.22			
	14.45	HC, ppmC	287	10.0	79.1	1.200
		LOW CO, ppm	0	—	61.4	
		CO, ppm	6481	30.5	60.7	
		NOX, ppm	1577	11.0	66.8	
		CO2, %	14.49			
		O2, %	0.32			

TABLE 19. TEST RESULTS FOR CONVERTER F2RA

TEST NO.	TARGET/ CALCULATED AIR-FUEL RATIO	EXHAUST CONSTITUENTS AND UNITS	CATALYST INLET CONCENTRATION	50% CONVERSION LIGHT-OFF TIME, (SEC)	EFFICIENCY, %	REDOX RATIO
F2RA	14.85	HC, ppmC	62		73.5	0.204
4/24/91	14.92	LOW CO, ppm	0		98.4	
		CO, ppm	2177		95.6	
		NOX, ppm	1277		14.4	
		CO2, %	14.49			
		O2, %	0.69			
	14.65	HC, ppmC	162		79.7	0.632
	14.65	LOW CO, ppm	0		87.1	
		CO, ppm	4448		86.3	
		NOX, ppm	1243		55.9	
		CO2, %	14.33			
		O2, %	0.44			
	14.55	HC, ppmC	212		81.9	0.721
	14.62	LOW CO, ppm	0		81.4	
		CO, ppm	5017		81.6	
		NOX, ppm	1243		58.8	
		CO2, %	14.49			
		O2, %	0.44			
	14.45	HC, ppmC	287		75.4	1.338
	14.44	LOW CO, ppm	0		64.9	
		CO, ppm	7010		61.7	
		NOX, ppm	1186		72.5	
		CO2, %	14.65			
		O2, %	0.32			
	14.4	HC, ppmC	299		74.6	1.498
	14.41	LOW CO, ppm	0		62.9	
		CO, ppm	7316		59.6	
		NOX, ppm	1163		74.1	
		CO2, %	14.65			
		O2, %	0.30			
	14.30	HC, ppmC	374		71.2	1.964
	14.33	LOW CO, ppm	0		--	
		CO, ppm	8887		40.9	
		NOX, ppm	1151		80.4	
		CO2, %	14.65			
		O2, %	0.27			
	14.45	HC, ppmC	299	15.0	76.4	1.472
		LOW CO, ppm	0	--	60.7	
		CO, ppm	7163	26.5	55.0	
		NOX, ppm	1151	13.5	75.0	
		CO2, %	14.49			
		O2, %	0.30			

TABLE 20. TEST RESULTS FOR CONVERTER F6LA

TEST NO.	TARGET/ CALCULATED AIR-FUEL RATIO	EXHAUST CONSTITUENTS AND UNITS	CATALYST INLET CONCENTRATION	50% CONVERSION LIGHT-OFF TIME, (SEC)	EFFICIENCY, %	REDOX RATIO
F6LA	14.85	HC, ppmC	85		-20.7	0.216
4/25/91	14.91	LOW CO, ppm	0		95.7	
		CO, ppm	2177		94.5	
		NOX, ppm	1254		23.7	
		CO2, %	14.02			
		O2, %	0.67			
	14.65	HC, ppmC	155		53.7	0.559
	14.67	LOW CO, ppm	0		71.5	
		CO, ppm	3888		73.0	
		NOX, ppm	1197		48.0	
		CO2, %	14.02			
		O2, %	0.44			
	14.55	HC, ppmC	232		59.5	0.940
	14.54	LOW CO, ppm	0		44.5	
		CO, ppm	5522		46.5	
		NOX, ppm	1140		56.2	
		CO2, %	14.17			
		O2, %	0.37			
	14.45	HC, ppmC	279		61.9	1.140
	14.49	LOW CO, ppm	0		--	
		CO, ppm	5814		35.1	
		NOX, ppm	1093		60.0	
		CO2, %	14.17			
		O2, %	0.32			
	14.4	HC, ppmC	314		61.8	1.490
	14.41	LOW CO, ppm	0		--	
		CO, ppm	7163		35.6	
		NOX, ppm	1093		62.3	
		CO2, %	14.17			
		O2, %	0.30			
	14.30	HC, ppmC	386		59.8	1.925
	14.33	LOW CO, ppm	0		--	
		CO, ppm	8567		31.0	
		NOX, ppm	1082		67.6	
		CO2, %	14.17			
		O2, %	0.27			
	14.45	HC, ppmC	299	19.5	64.1	1.381
		LOW CO, ppm	0	--	--	
		CO, ppm	6632	NA	35.7	
		NOX, ppm	1105	16.0	62.7	
		CO2, %	14.02			
		O2, %	0.30			

TABLE 21. TEST RESULTS FOR CONVERTER F6RA

TEST NO.	TARGET/ CALCULATED AIR-FUEL RATIO	EXHAUST CONSTITUENTS AND UNITS	CATALYST INLET CONCENTRATION	50% CONVERSION LIGHT-OFF TIME, (SEC)	EFFICIENCY, %	REDOX RATIO
F6RA	14.85	HC, ppmC	67		82.0	0.200
4/24/91	14.90	LOW CO, ppm	0		94.1	
		CO, ppm	2041		97.1	
		NOX, ppm	1243		20.1	
		CO2, %	14.81			
		O2, %	0.67			
	14.65	HC, ppmC	147		73.2	0.506
	14.70	LOW CO, ppm	0		69.8	
		CO, ppm	3888		71.4	
		NOX, ppm	1209		41.3	
		CO2, %	14.49			
		O2, %	0.49			
	14.55	HC, ppmC	224		66.6	0.911
	14.55	LOW CO, ppm	0		51.1	
		CO, ppm	5377		52.6	
		NOX, ppm	1174		50.1	
		CO2, %	14.49			
		O2, %	0.37			
	14.45	HC, ppmC	287		62.9	1.240
	14.46	LOW CO, ppm	0		--	
		CO, ppm	6481		41.8	
		NOX, ppm	1220		56.0	
		CO2, %	14.49			
		O2, %	0.32			
	14.4	HC, ppmC	304		60.2	1.438
	14.42	LOW CO, ppm	0		--	
		CO, ppm	7010		36.2	
		NOX, ppm	1186		57.9	
		CO2, %	14.49			
		O2, %	0.30			
	14.30	HC, ppmC	364		57.9	1.860
	14.34	LOW CO, ppm	0		--	
		CO, ppm	8408		32.3	
		NOX, ppm	1163		61.3	
		CO2, %	14.49			
		O2, %	0.27			
	14.45	HC, ppmC	274	20.0	62.7	1.202
		LOW CO, ppm	0	NA	--	
		CO, ppm	6258	NA	37.5	
		NOX, ppm	1186	26.0	56.9	
		CO2, %	14.49			
		O2, %	0.32			

TABLE 22. TEST RESULTS FOR CONVERTER T-1

TEST NO.	TARGET/ CALCULATED AIR-FUEL RATIO	EXHAUST CONSTITUENTS AND UNITS	CATALYST INLET CONCENTRATION	50% CONVERSION LIGHT-OFF TIME, (SEC)	EFFICIENCY, %	REDOX RATIO
T-1	14.85	HC, ppmC	87		83.6	0.262
4/1/91	14:86	LOW CO, ppm	0		99.0	
		CO, ppm	2652		—	
		NOX, ppm	1611		22.9	
		CO2, %	14.49			
		O2, %	0.64			
	14.65	HC, ppmC	150		88.9	0.497
	14.70	LOW CO, ppm	0		99.5	
		CO, ppm	3958		—	
		NOX, ppm	1611		52.9	
		CO2, %	14.65			
		O2, %	0.49			
	14.55	HC, ppmC	219		91.0	0.869
	14.55	LOW CO, ppm	0		98.9	
		CO, ppm	5377		—	
		NOX, ppm	1577		72.3	
		CO2, %	14.49			
		O2, %	0.37			
	14.45	HC, ppmC	274		90.0	1.128
	14.48	LOW CO, ppm	0		93.3	
		CO, ppm	6556		89.6	
		NOX, ppm	1543		84.6	
		CO2, %	14.49			
		O2, %	0.35			
	14.4	HC, ppmC	299		87.2	1.266
	14.44	LOW CO, ppm	0		85.0	
		CO, ppm	6934		76.3	
		NOX, ppm	1566		89.6	
		CO2, %	14.33			
		O2, %	0.32			
	14.30	HC, ppmC	324		87.8	1.722
	14.37	LOW CO, ppm	0		80.1	
		CO, ppm	7625		58.2	
		NOX, ppm	1510		95.8	
		CO2, %	14.65			
		O2, %	0.25			
	14.45	HC, ppmC	312	15.5	87.7	1.362
		LOW CO, ppm	0	—	—	
		CO, ppm	7163	19.5	80.7	
		NOX, ppm	1555	11.8	90.3	
		CO2, %	14.39			
		O2, %	0.31			

TABLE 23.- TEST RESULTS FOR CONVERTER T-2

TEST NO.	TARGET/ CALCULATED AIR-FUEL RATIO	EXHAUST CONSTITUENTS AND UNITS	CATALYST INLET CONCENTRATION	50% CONVERSION LIGHT-OFF TIME, (SEC)	EFFICIENCY, %	REDOX RATIO
T-2	14.85	HC, ppmC	87		81.0	0.250
4/1/91	14.87	LOW CO, ppm	0		99.3	
		CO, ppm	2516		--	
		NOX, ppm	1622		21.9	
		CO2, %	14.42			
		O2, %	0.64			
	14.65	HC, ppmC	174		90.5	0.537
	14.69	LOW CO, ppm	0		99.0	
		CO, ppm	4237		--	
		NOX, ppm	1588		56.1	
		CO2, %	14.42			
		O2, %	0.49			
	14.55	HC, ppmC	212		92.2	0.771
	14.58	LOW CO, ppm	0		97.2	
		CO, ppm	5017		--	
		NOX, ppm	1577		66.8	
		CO2, %	14.49			
		O2, %	0.40			
	14.45	HC, ppmC	237		88.4	1.018
	14.51	LOW CO, ppm	0		89.2	
		CO, ppm	5961		--	
		NOX, ppm	1566		72.1	
		CO2, %	14.49			
		O2, %	0.35			
	14.4	HC, ppmC	299		89.0	1.311
	14.44	LOW CO, ppm	0		83.0	
		CO, ppm	6707		79.4	
		NOX, ppm	1555		78.3	
		CO2, %	14.49			
		O2, %	0.30			
	14.30	HC, ppmC	374		85.4	2.096
	14.31	LOW CO, ppm	0		77.3	
		CO, ppm	8567		61.1	
		NOX, ppm	1521		89.3	
		CO2, %	14.49			
		O2, %	0.22			
	14.45	HC, ppmC	262	20.5	87.4	1.071
		LOW CO, ppm	0	21.0	84.3	
		CO, ppm	6258	--	--	
		NOX, ppm	1588	21.0	72.5	
		CO2, %	14.65			
		O2, %	0.35			

TABLE 24. TEST RESULTS FOR CONVERTER T-3

TEST NO.	TARGET/ CALCULATED AIR-FUEL RATIO	EXHAUST CONSTITUENTS AND UNITS	CATALYST INLET CONCENTRATION	50% CONVERSION LIGHT-OFF TIME, (SEC)	EFFICIENCY, %	REDOX RATIO
T-3	14.85	HC, ppmC	75		77.9	0.207
4/03/91	14.89	LOW CO, ppm	0		99.0	
		CO, ppm	2041		—	
		NOX, ppm	1355		21.2	
		CO2, %	14.49			
		O2, %	0.64			
	14.65	HC, ppmC	150		88.9	0.501
	14.70	LOW CO, ppm	0		98.9	
		CO, ppm	3680		—	
		NOX, ppm	1288		51.6	
		CO2, %	14.49			
		O2, %	0.47			
	14.55	HC, ppmC	199		89.0	0.900
	14.55	LOW CO, ppm	0		98.4	
		CO, ppm	5089		—	
		NOX, ppm	1265		72.3	
		CO2, %	14.65			
		O2, %	0.35			
	14.45	HC, ppmC	299		87.2	1.375
	14.44	LOW CO, ppm	0		86.7	
		CO, ppm	6258		86.1	
		NOX, ppm	1265		78.2	
		CO2, %	14.49			
		O2, %	0.27			
	14.4	HC, ppmC	299		87.2	1.470
	14.42	LOW CO, ppm	0		88.6	
		CO, ppm	6707		85.1	
		NOX, ppm	1243		85.8	
		CO2, %	14.49			
		O2, %	0.27			
	14.30	HC, ppmC	361		83.4	1.918
	14.34	LOW CO, ppm	0		73.2	
		CO, ppm	8093		64.8	
		NOX, ppm	1231		92.8	
		CO2, %	14.49			
		O2, %	0.25			
	14.45	HC, ppmC	287	19.0	86.6	1.194
		LOW CO, ppm	0	—	88.5	
		CO, ppm	6258	30.0	86.1	
		NOX, ppm	1265	18.0	78.2	
		CO2, %	14.49			
		O2, %	0.32			

TABLE 25. TEST RESULTS FOR CONVERTER T-4

TEST NO.	TARGET/ CALCULATED AIR-FUEL RATIO	EXHAUST CONSTITUENTS AND UNITS	CATALYST INLET CONCENTRATION	50% CONVERSION LIGHT-OFF TIME, (SEC)	EFFICIENCY, %	REDOX RATIO
T-4	14.85	HC, ppmC	62		82.3	0.204
4/03/91	14.90	LOW CO, ppm	0		99.3	
		CO, ppm	2041		—	
		NOX, ppm	1366		18.2	
		CO2, %	14.33			
		O2, %	0.64			
	14.65	HC, ppmC	125		86.7	0.483
	14.70	LOW CO, ppm	0		98.9	
		CO, ppm	3611		—	
		NOX, ppm	1332		50.5	
		CO2, %	14.33			
		O2, %	0.47			
	14.55	HC, ppmC	187		91.2	0.892
	14.55	LOW CO, ppm	0		99.0	
		CO, ppm	5089		—	
		NOX, ppm	1299		71.1	
		CO2, %	14.33			
		O2, %	0.35			
	14.45	HC, ppmC	336		87.0	1.700
	14.37	LOW CO, ppm	0		79.9	
		CO, ppm	7780		79.7	
		NOX, ppm	1243		97.0	
		CO2, %	14.33			
		O2, %	0.27			
	14.4	HC, ppmC	299		87.2	1.548
	14.41	LOW CO, ppm	0		87.8	
		CO, ppm	7010		89.4	
		NOX, ppm	1163		90.3	
		CO2, %	14.33			
		O2, %	0.27			
	14.30	HC, ppmC	361		84.9	1.875
	14.35	LOW CO, ppm	0		82.1	
		CO, ppm	7780		78.9	
		NOX, ppm	1151		97.8	
		CO2, %	14.17			
		O2, %	0.25			
	14.45	HC, ppmC	324	25.0	79.9	1.820
		LOW CO, ppm	0	—	66.1	
		CO, ppm	7625	46.0	58.2	
		NOX, ppm	1163	16.5	94.6	
		CO2, %	14.33			
		O2, %	0.25			

TABLE 26. TEST RESULTS FOR CONVERTER T-5

TEST NO.	TARGET/ CALCULATED AIR-FUEL RATIO	EXHAUST CONSTITUENTS AND UNITS	CATALYST INLET CONCENTRATION	50% CONVERSION LIGHT-OFF TIME, (SEC)	EFFICIENCY, %	REDOX RATIO
T-5	14.85	HC, ppmC	50		80.1	0.183
4/4/91	14.96	LOW CO, ppm	0		98.2	
		CO, ppm	2109		—	
		NOX, ppm	1377		14.3	
		CO2, %	14.33			
		O2, %	0.74			
	14.65	HC, ppmC	125		84.1	0.520
	14.68	LOW CO, ppm	0		97.8	
		CO, ppm	3749		—	
		NOX, ppm	1421		51.0	
		CO2, %	14.49			
		O2, %	0.44			
	14.55	HC, ppmC	174		86.1	0.802
	14.57	LOW CO, ppm	0		98.1	
		CO, ppm	4589		96.3	
		NOX, ppm	1344		66.5	
		CO2, %	14.49			
		O2, %	0.35			
	14.45	HC, ppmC	287		84.7	1.549
	14.40	LOW CO, ppm	0		—	
		CO, ppm	7163		83.4	
		NOX, ppm	1265		93.0	
		CO2, %	14.33			
		O2, %	0.27			
	14.4	HC, ppmC	299		85.4	1.568
	14.40	LOW CO, ppm	0		—	
		CO, ppm	7239		84.4	
		NOX, ppm	1277		92.1	
		CO2, %	14.33			
		O2, %	0.27			
	14.30	HC, ppmC	336		79.7	2.325
	14.30	LOW CO, ppm	0		—	
		CO, ppm	8329		56.7	
		NOX, ppm	1243		92.3	
		CO2, %	14.33			
		O2, %	0.20			
	14.45	HC, ppmC	249	20.5	84.6	1.541
		LOW CO, ppm	0	—	86.9	
		CO, ppm	6556	23.5	83.4	
		NOX, ppm	1299	14.0	89.3	
		CO2, %	14.33			
		O2, %	0.24			

TABLE 27. TEST RESULTS FOR CONVERTER T-6

TEST NO.	TARGET/ CALCULATED AIR-FUEL RATIO	EXHAUST CONSTITUENTS AND UNITS	CATALYST INLET CONCENTRATION	50% CONVERSION LIGHT-OFF TIME, (SEC)	EFFICIENCY, %	REDOX RATIO
T-6	14.85	HC, ppmC	50		80.1	0.217
4/4/91	14.90	LOW CO, ppm	0		97.3	
		CO, ppm	2217		—	
		NOX, ppm	1432		15.6	
		CO2, %	14.17			
		O2, %	0.64			
	14.65	HC, ppmC	137		86.3	0.625
	14.64	LOW CO, ppm	0		96.5	
		CO, ppm	4307		—	
		NOX, ppm	1421		55.3	
		CO2, %	14.33			
		O2, %	0.42			
	14.55	HC, ppmC	179		87.1	0.867
	14.55	LOW CO, ppm	0		95.6	
		CO, ppm	5232		—	
		NOX, ppm	1432		68.6	
		CO2, %	14.33			
		O2, %	0.36			
	14.45	HC, ppmC	287		86.6	1.400
	14.43	LOW CO, ppm	0		91.0	
		CO, ppm	7010		86.7	
		NOX, ppm	1344		86.0	
		CO2, %	14.49			
		O2, %	0.30			
	14.4	HC, ppmC	262		84.1	1.583
	14.40	LOW CO, ppm	0		86.3	
		CO, ppm	6934		81.9	
		NOX, ppm	1377		87.2	
		CO2, %	14.42			
		O2, %	0.25			
	14.30	HC, ppmC	324		81.5	2.021
	14.33	LOW CO, ppm	0		78.3	
		CO, ppm	8093		69.8	
		NOX, ppm	1355		90.7	
		CO2, %	14.33			
		O2, %	0.22			
	14.45	HC, ppmC	254	27.0	82.8	1.587
		LOW CO, ppm	0	—	85.1	
		CO, ppm	7010	36.0	86.7	
		NOX, ppm	1410	17.5	82.2	
		CO2, %	14.33			
		O2, %	0.25			

TABLE 28. EXHAUST SYSTEM REACTION CHECK

Test Dates: 4/23/91 and 5/2/91

Cat. in Temp. Deg. F	Target Air-Fuel Ratio	Exhaust Constituents and Units	Exhaust Port Concentration	Catalyst Inlet Concentration	Change, %	Port Redox Ratio	Cat in Redox Ratio
750	14.85	HC, ppmC	623	87	-86.0	0.380	0.186
		CO, ppm	3473	1771	-49.0		
		NO_x, ppm	578	575	-0.5		
		CO_2, %	14.33	14.49	+1.1		
		O_2, %	0.83	0.68	-18.2		
750	14.3	HC, ppmC	860	349	-59.4	0.961	0.925
		CO, ppm	8250	6707	-18.7		
		NO_x, ppm	596	564	-5.3		
		CO_2, %	14.33	14.49	-1.1		
		O_2, %	0.68	0.51	-24.4		
930	14.85	HC, ppmC	1209	37	-96.9	0.425	0.113
		CO, ppm	4420	1230	-72.2		
		NO_x, ppm	1345	1469	+9.2		
		CO_2, %	14.33	14.65	+2.2		
		O_2, %	1.05	0.70	-33.3		
930	14.65	HC, ppmC	1134	60	-94.7	0.597	0.254
		CO, ppm	4874	1906	-60.9		
		NO_x, ppm	1266	1323	+4.5		
		CO_2, %	14.49	14.81	+2.2		
		O_2, %	0.76	0.47	-38.6		
930	14.3	HC, ppmC	1496	287	-80.8	1.274	1.565
		CO, ppm	9289	6782	-27.0		
		NO_x, ppm	1209	1312	+8.5		
		CO_2, %	14.20	14.65	+3.1		
		O_2, %	0.60	0.25	-58.3		

TABLE 29. CO EFFICIENCY SPREAD FOR QA CONVERTER TESTS

Redox Ratio	CO % Efficiency Spread
0.6	0.2
0.8	0.2
0.1	<3.5
1.2	3.5
1.4	3.5
1.6	3.0
1.8	3.0
2.0	4.0

FIGURES

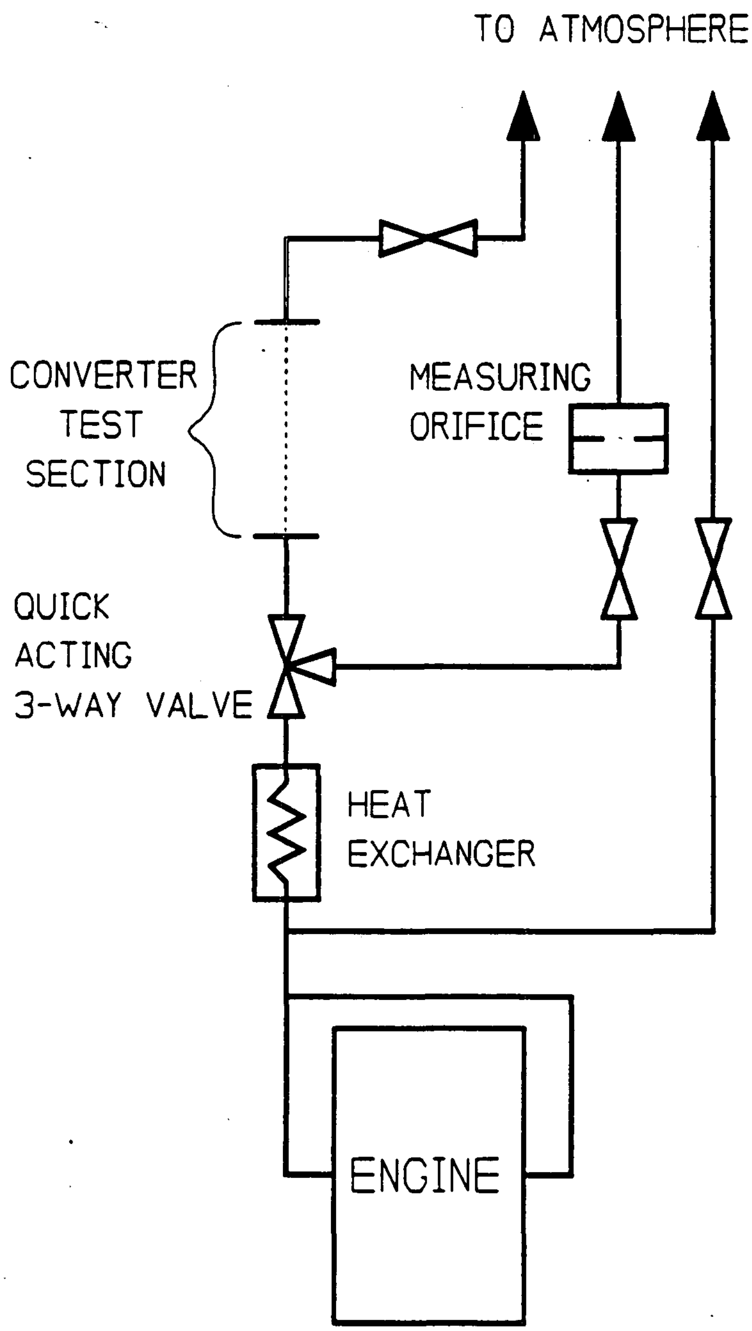

FIGURE 1. SCHEMATIC OF SLAVE ENGINE EXHAUST SYSTEM

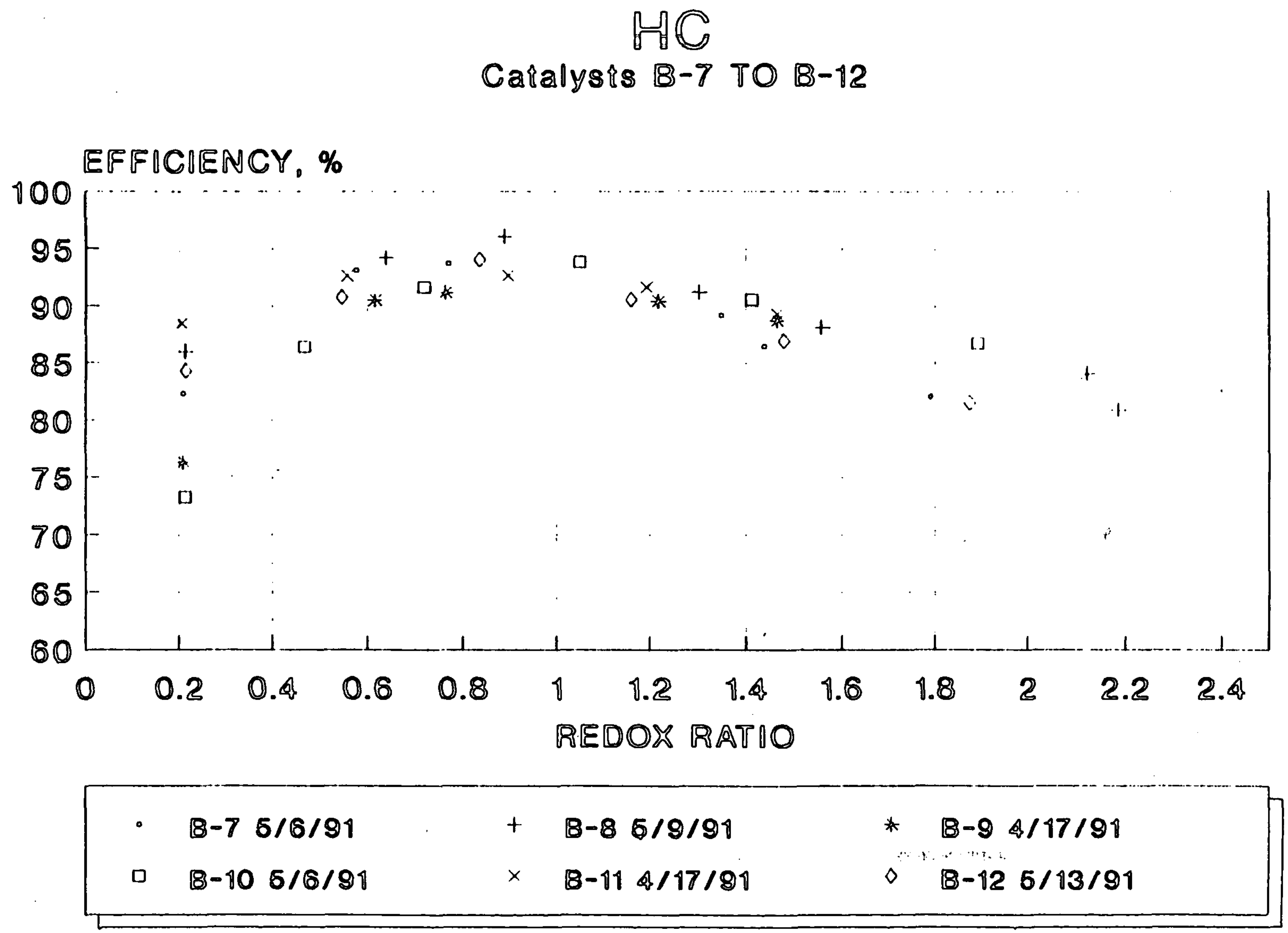

FIGURE 2. HC EMISSIONS FROM CONVERTERS B-7 TO B-12

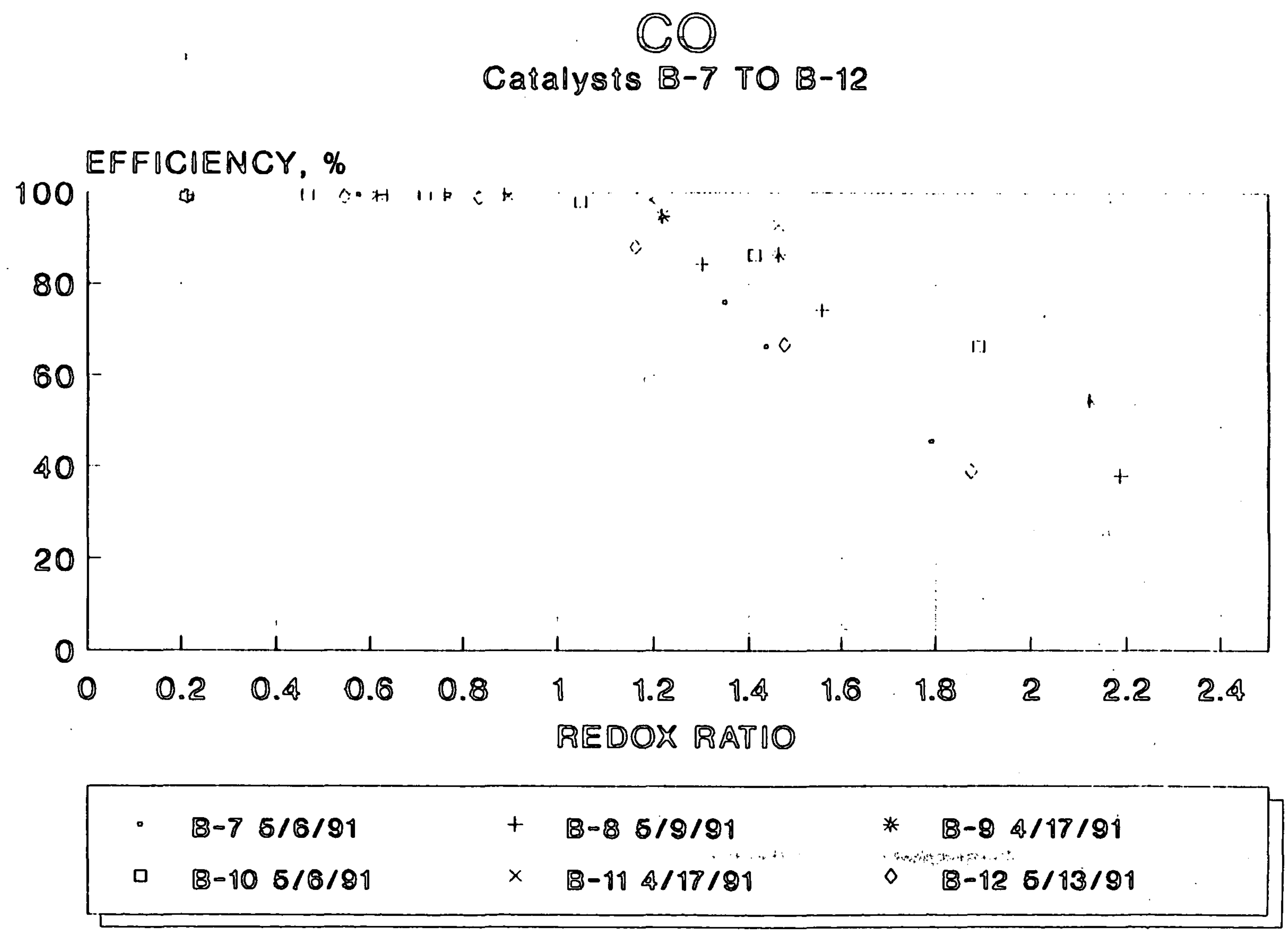

FIGURE 3. CO EMISSIONS FROM CONVERTERS B-7 TO B-12

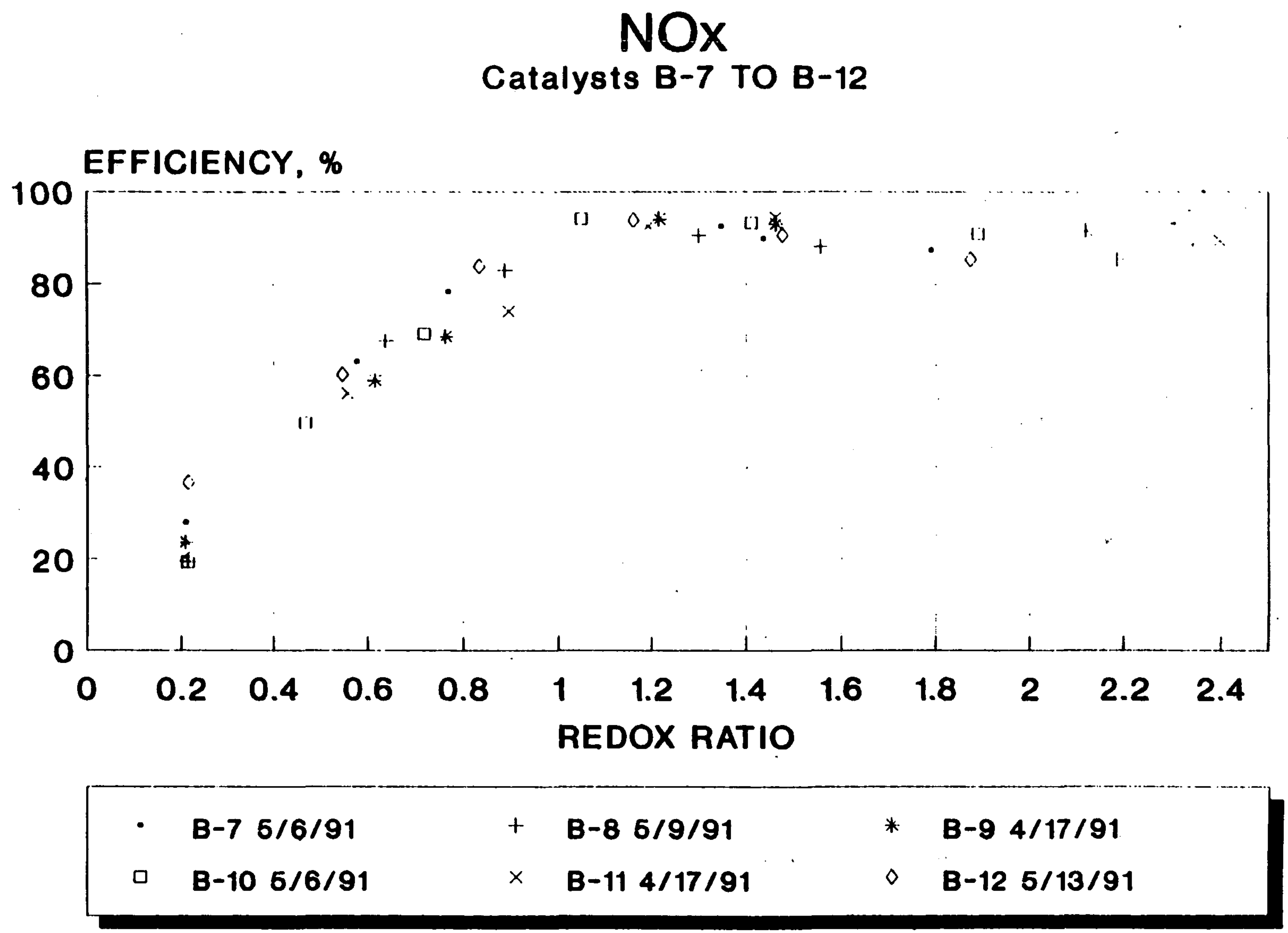

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FIGURE 4. NO_X EMISSIONS FROM CONVERTERS B-7 TO B-12

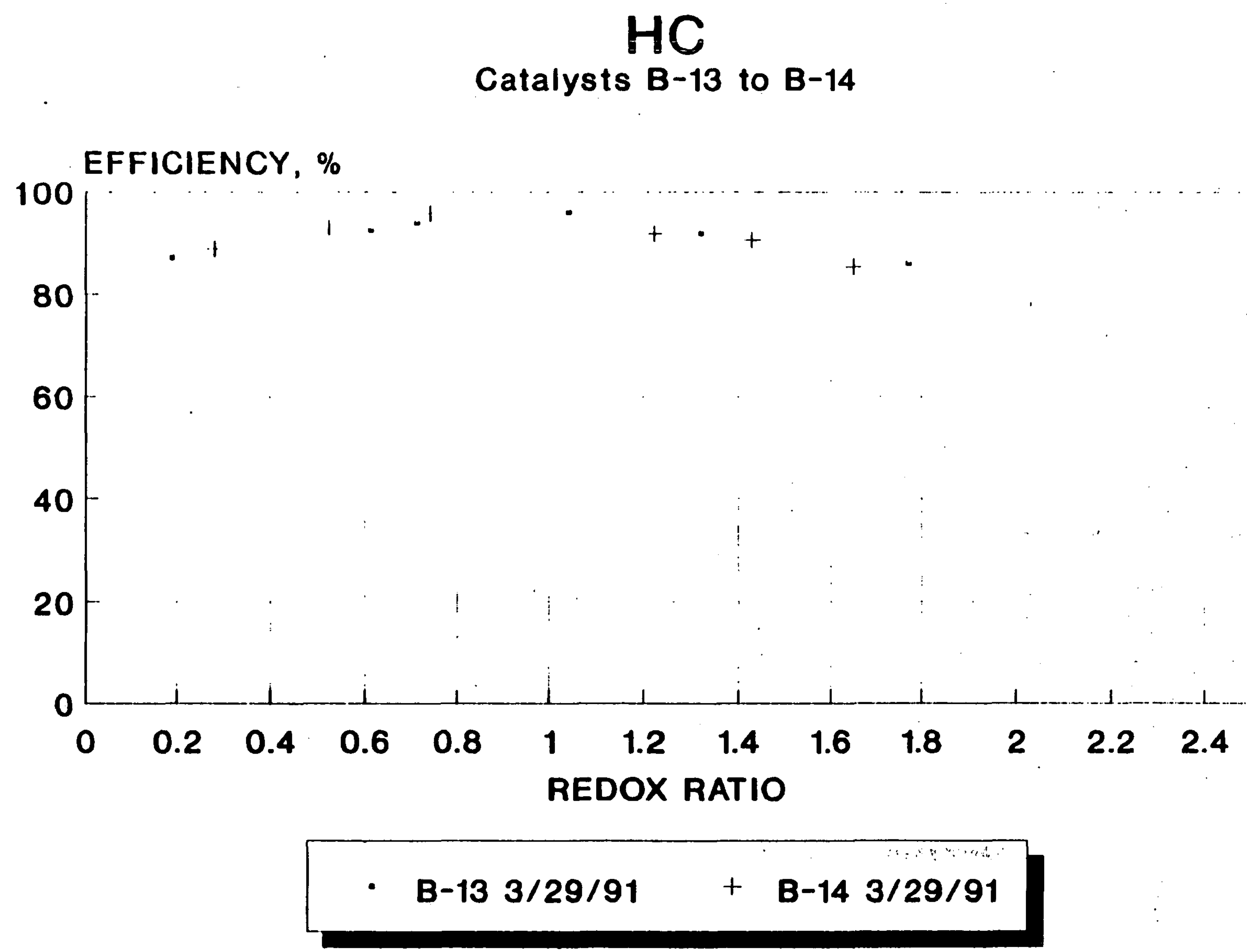


FIGURE 5. HC EMISSIONS FROM CONVERTERS B-13 TO B-14

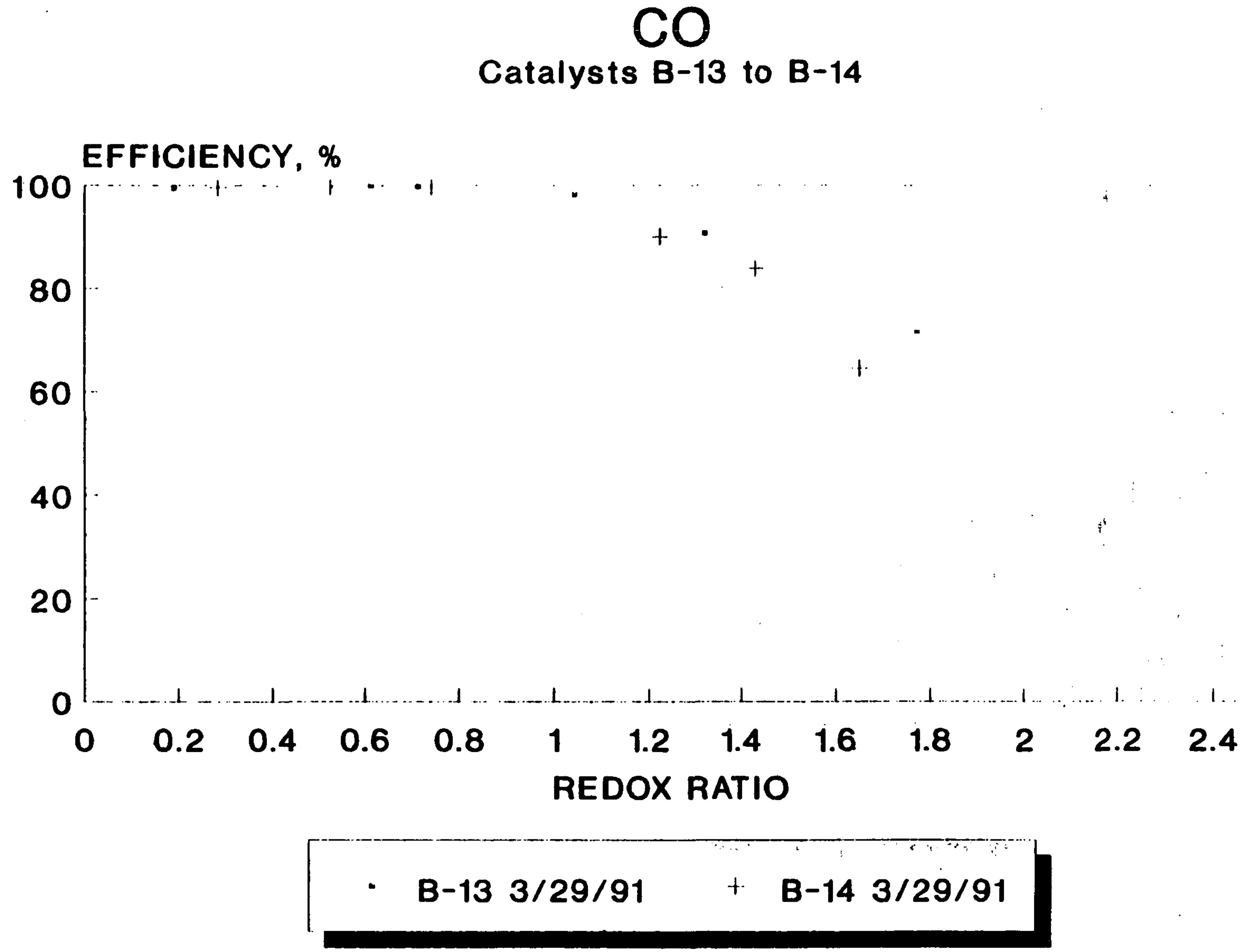


FIGURE 6. CO EMISSIONS FROM CONVERTERS B-13 TO B-14

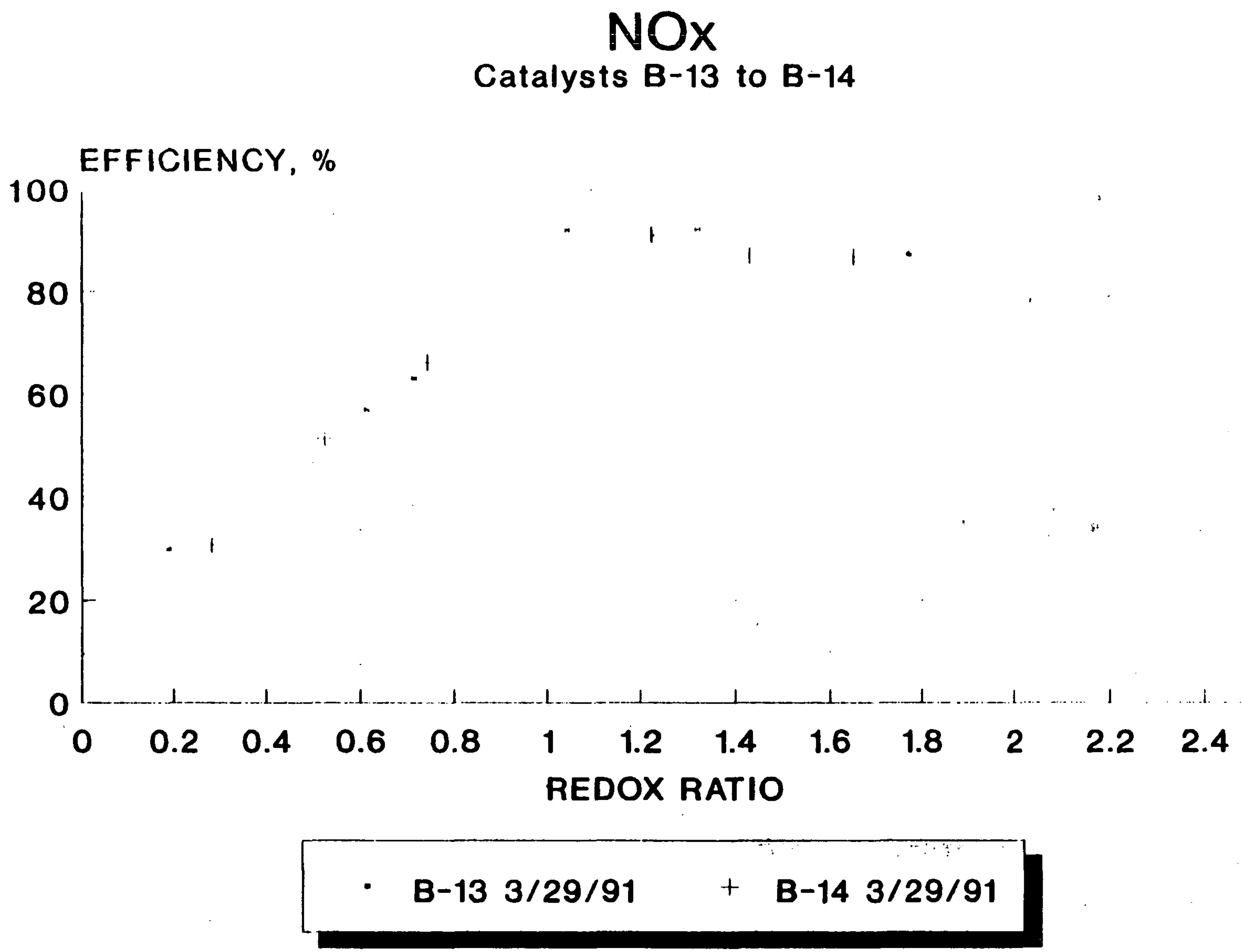


FIGURE 7. NO_x EMISSIONS FROM CONVERTERS B-13 TO B-14

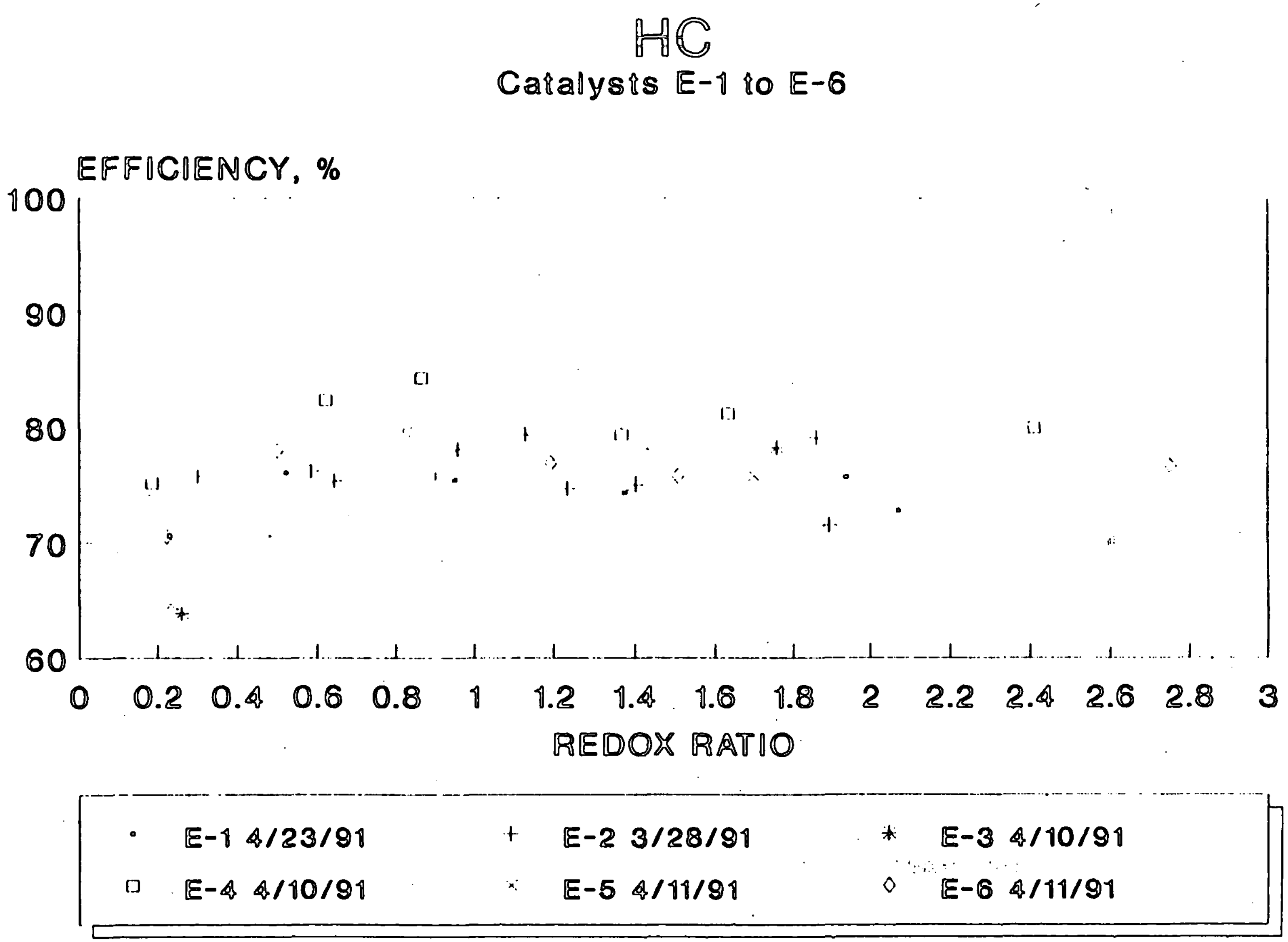


FIGURE 8. HC EMISSIONS FROM CONVERTERS E-1 TO E-6

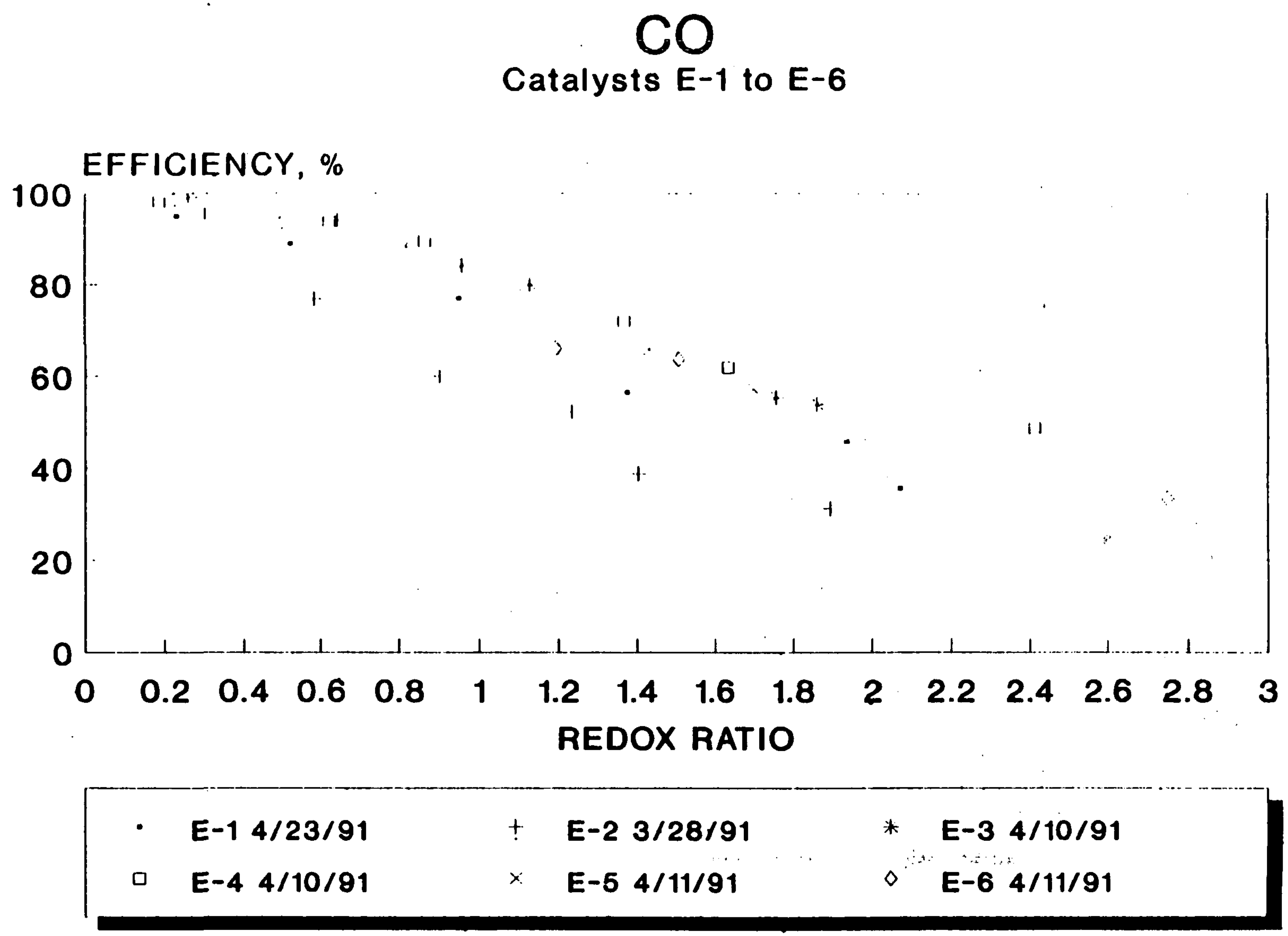


FIGURE 9. CO EMISSIONS FROM CONVERTERS E-1 TO E-6

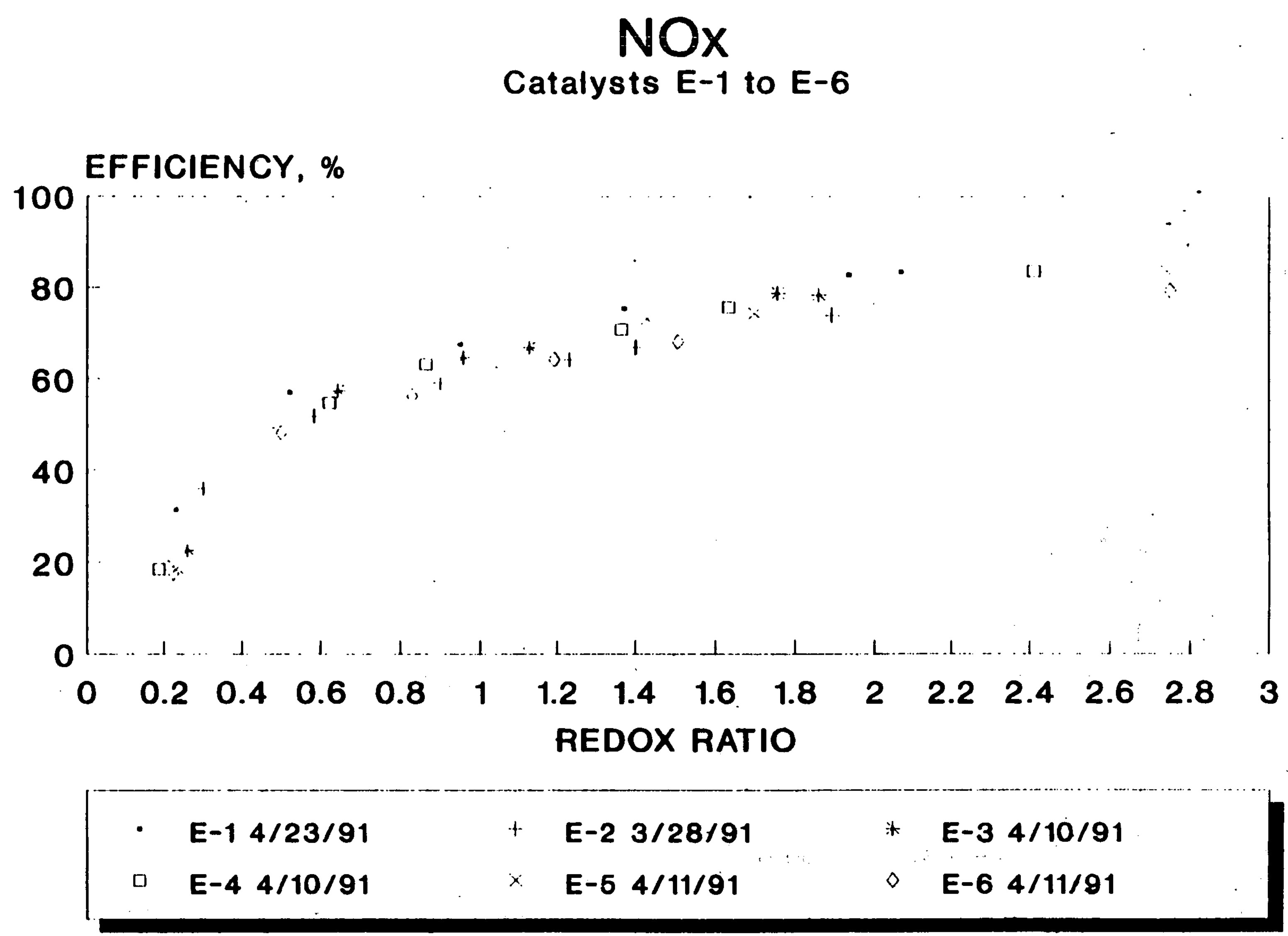


FIGURE 10. NO_X EMISSIONS FROM CONVERTERS E-1 TO E-6

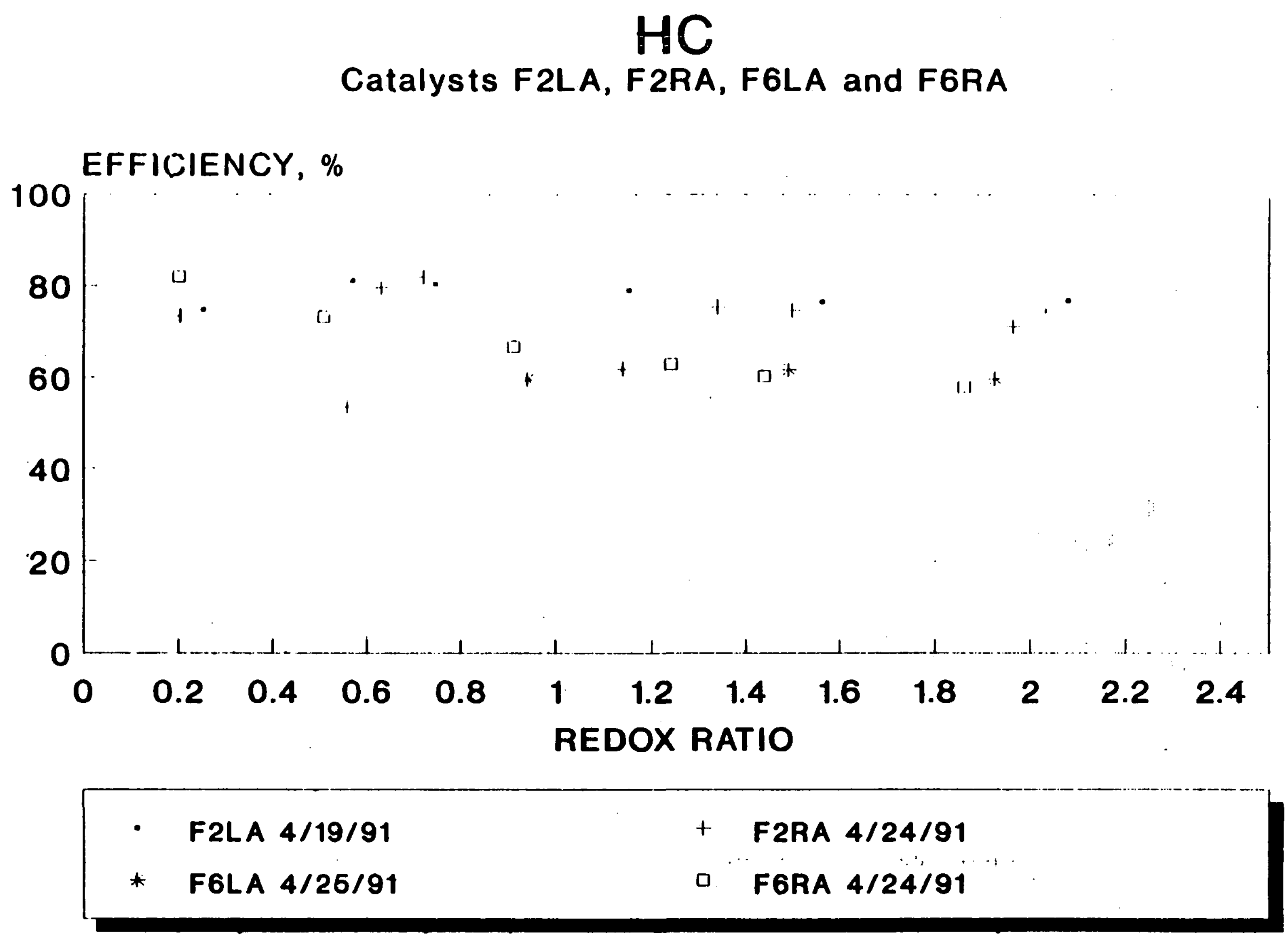


FIGURE 11. HC EMISSIONS FROM CONVERTERS F2LA, F2RA, F6LA AND F6RA

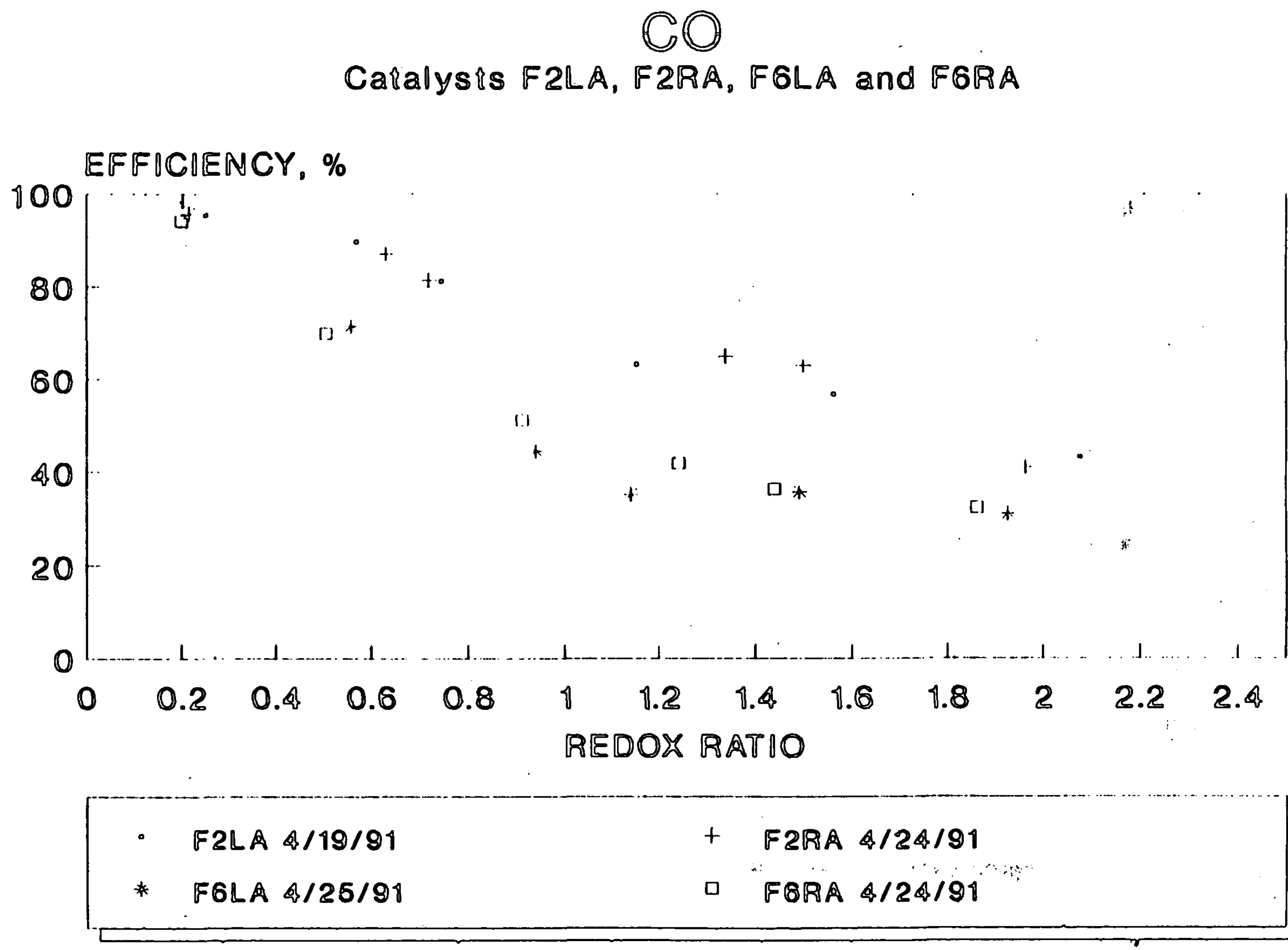


FIGURE 12. CO EMISSIONS FROM CONVERTERS F2LA, F2RA, F6LA AND F6RA

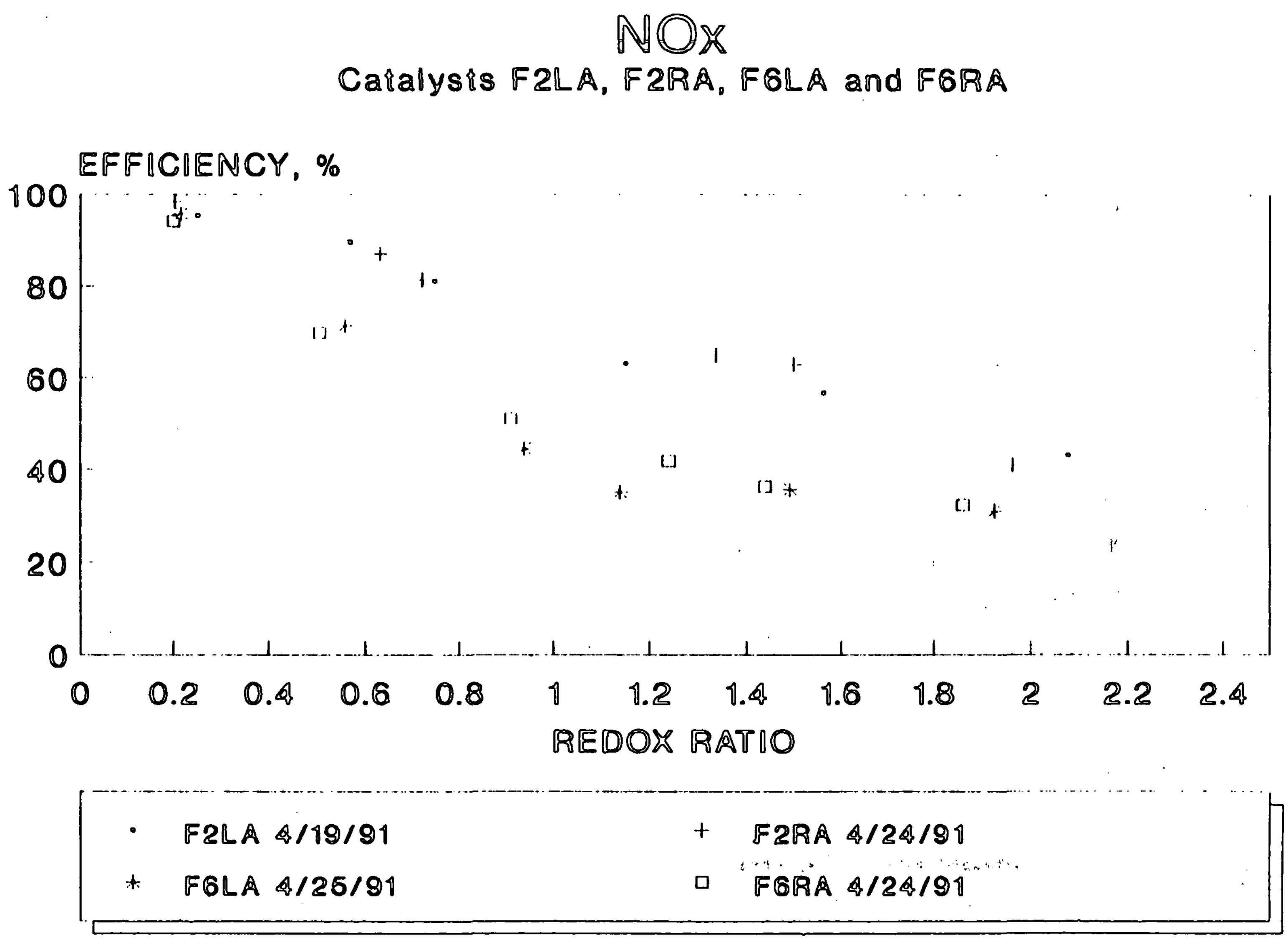


FIGURE 13. NO_X EMISSIONS FROM CONVERTERS F2LA, F2RA, F6LA AND F6RA

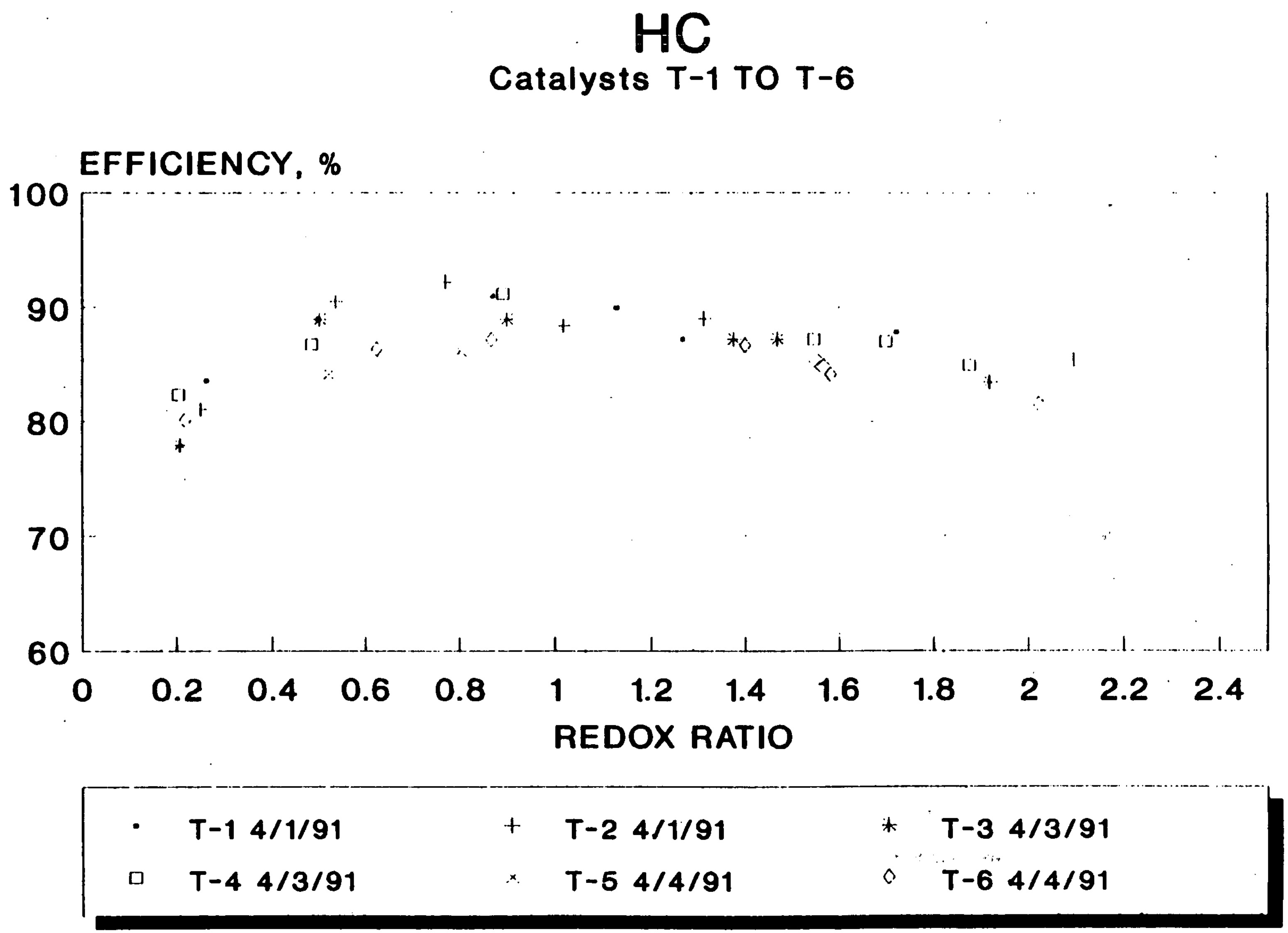


FIGURE 14. HC EMISSIONS FROM CONVERTERS T-1 TO T-6

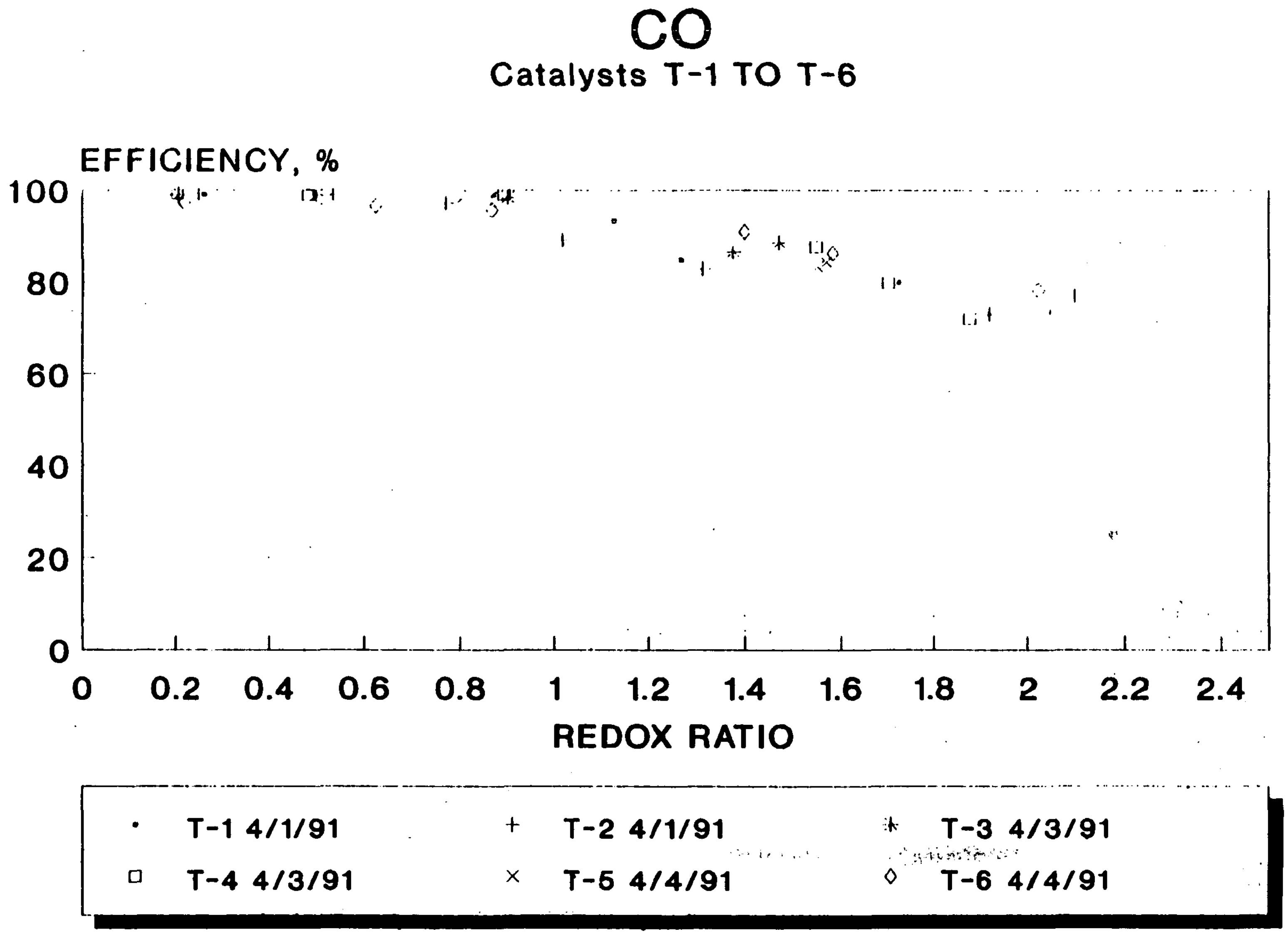
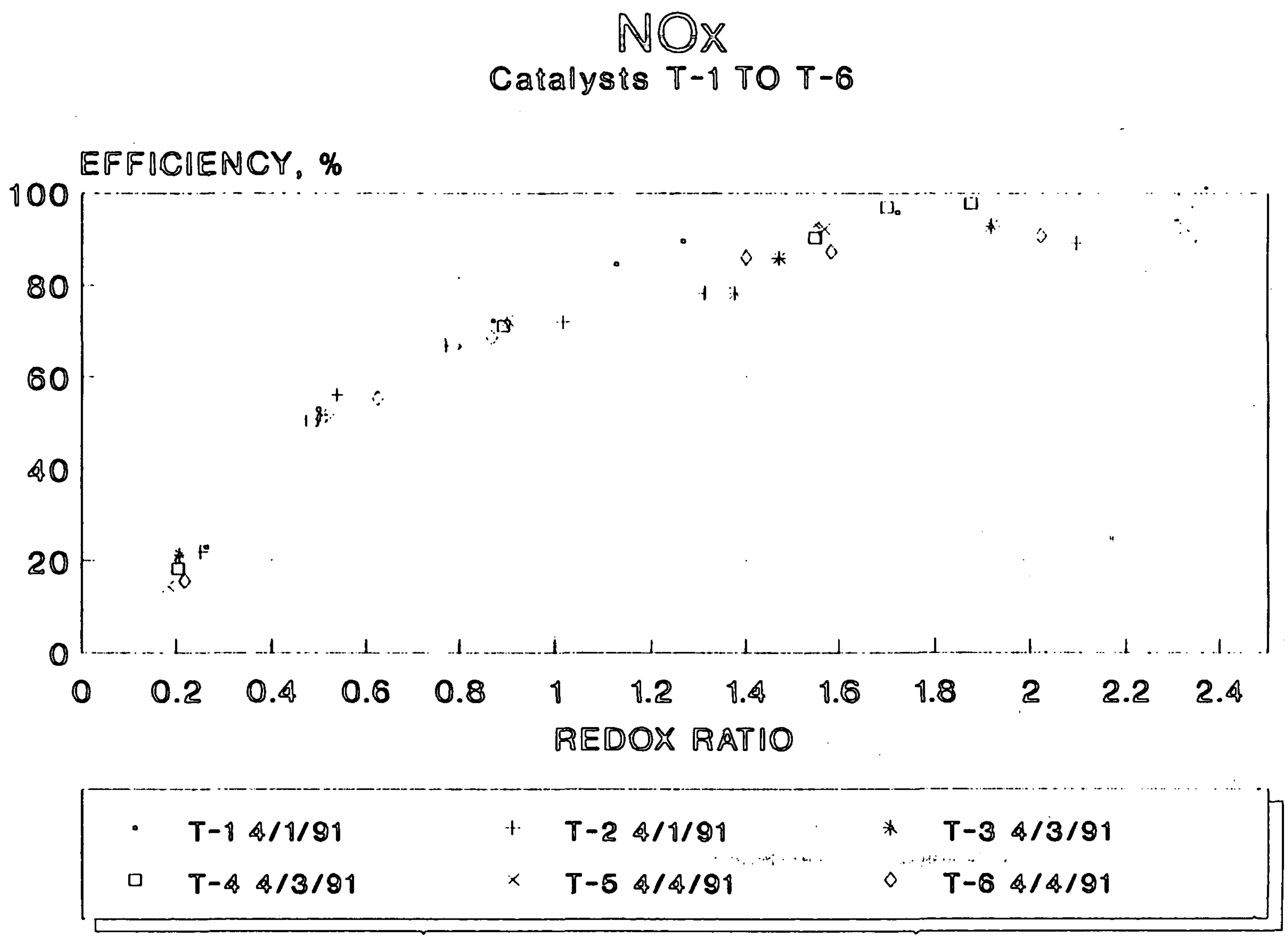


FIGURE 15. CO EMISSIONS FROM CONVERTERS T-1 TO T-6



54

FIGURE 16. NO_X EMISSIONS FROM CONVERTERS T-1 TO T-6

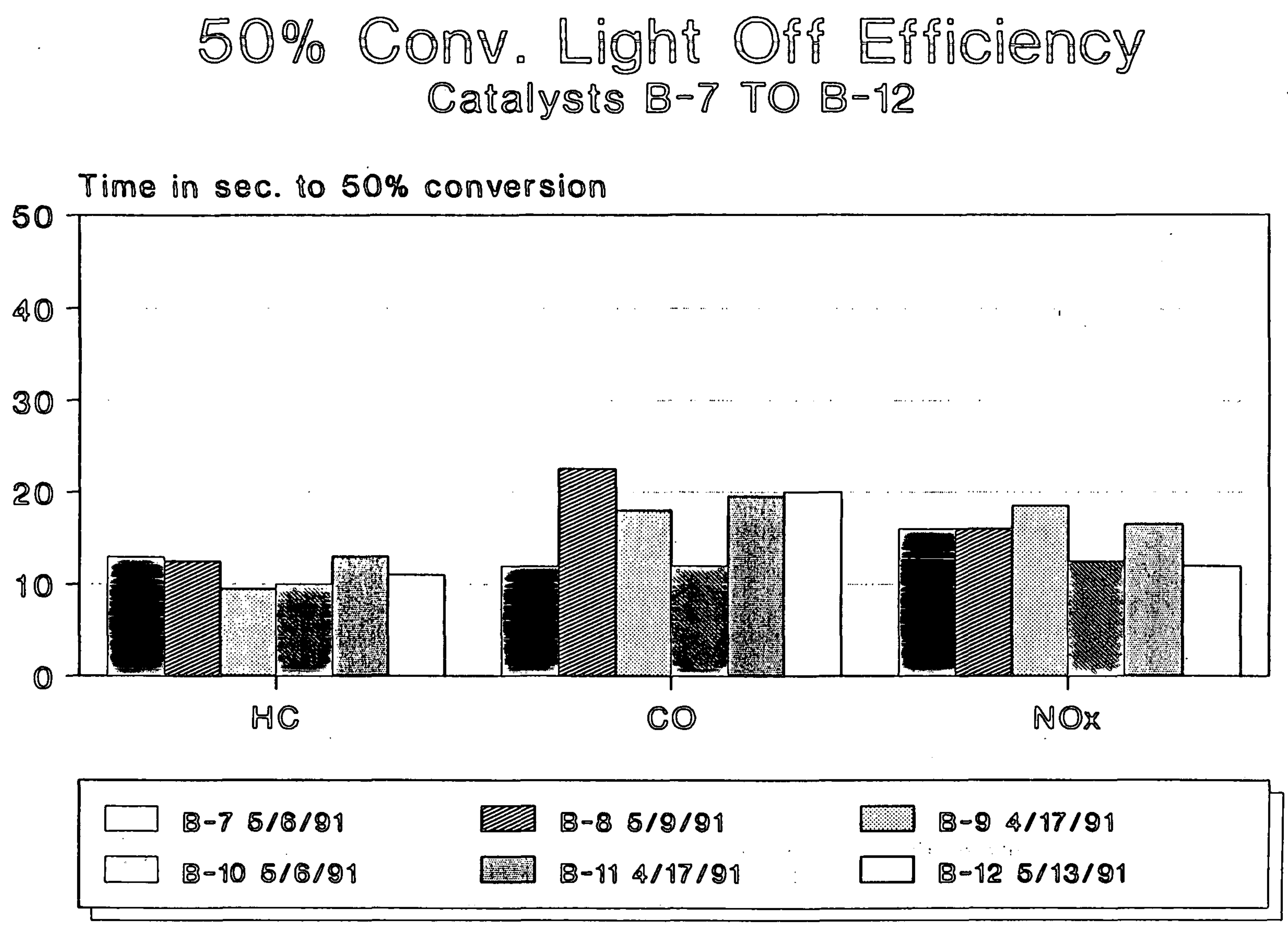


FIGURE 17. 50% LIGHT-OFF EFFICIENCY FOR CONVERTERS B-7 TO B-12

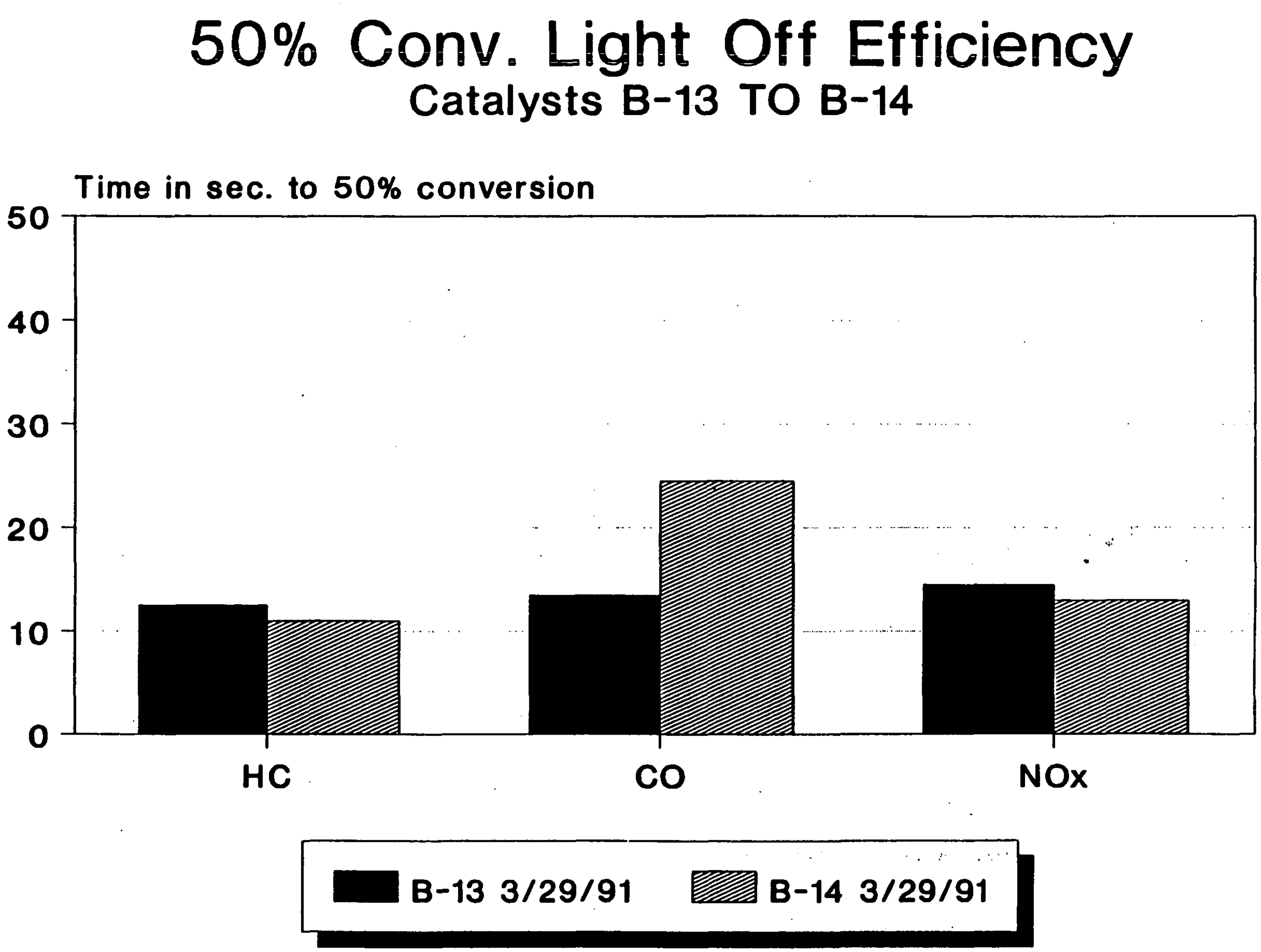


FIGURE 18. 50% LIGHT-OFF EFFICIENCY FOR CONVERTERS B-13 TO B-14

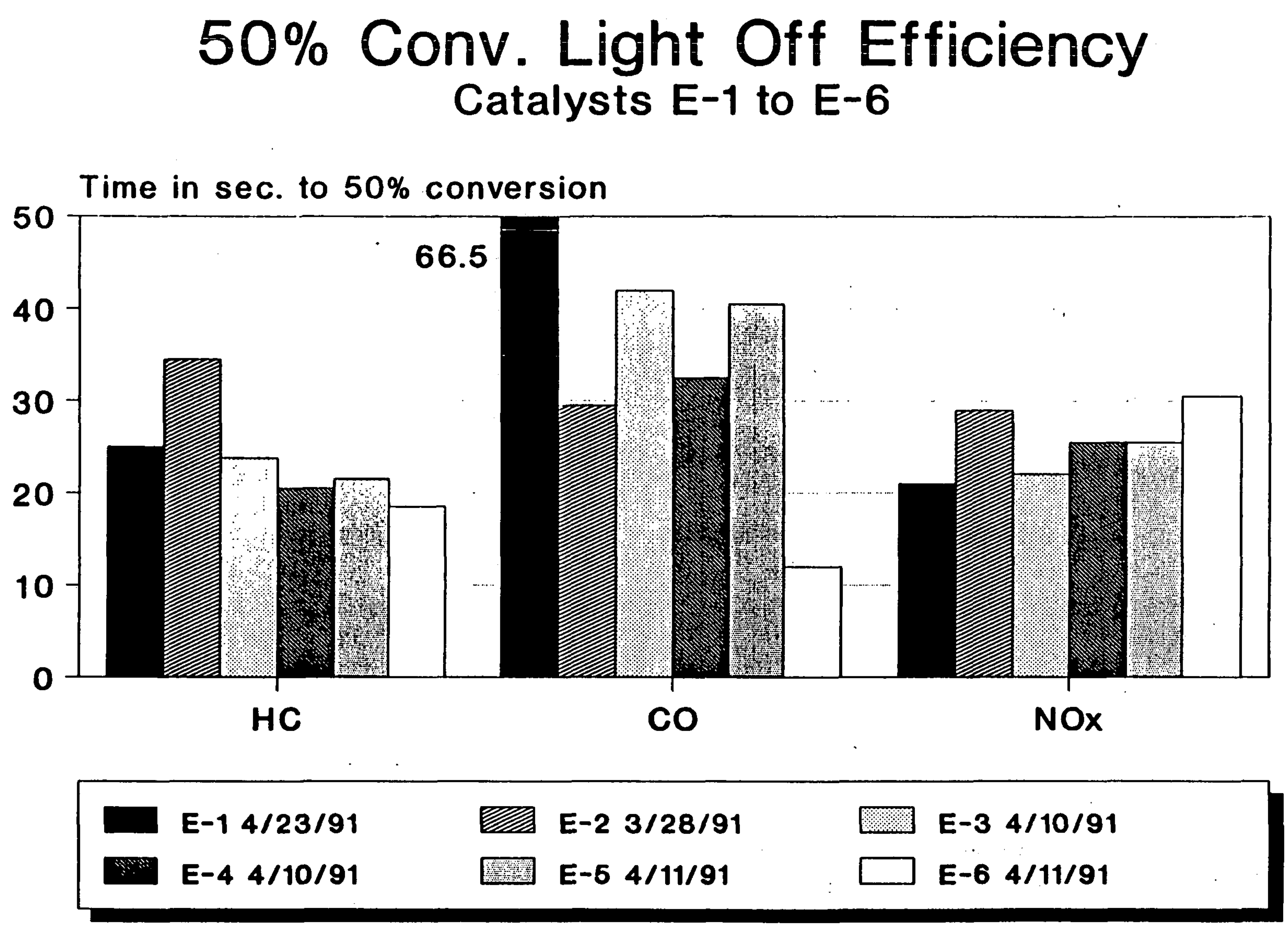


FIGURE 19. 50% LIGHT-OFF EFFICIENCY FOR CONVERTERS E-1 TO E-6

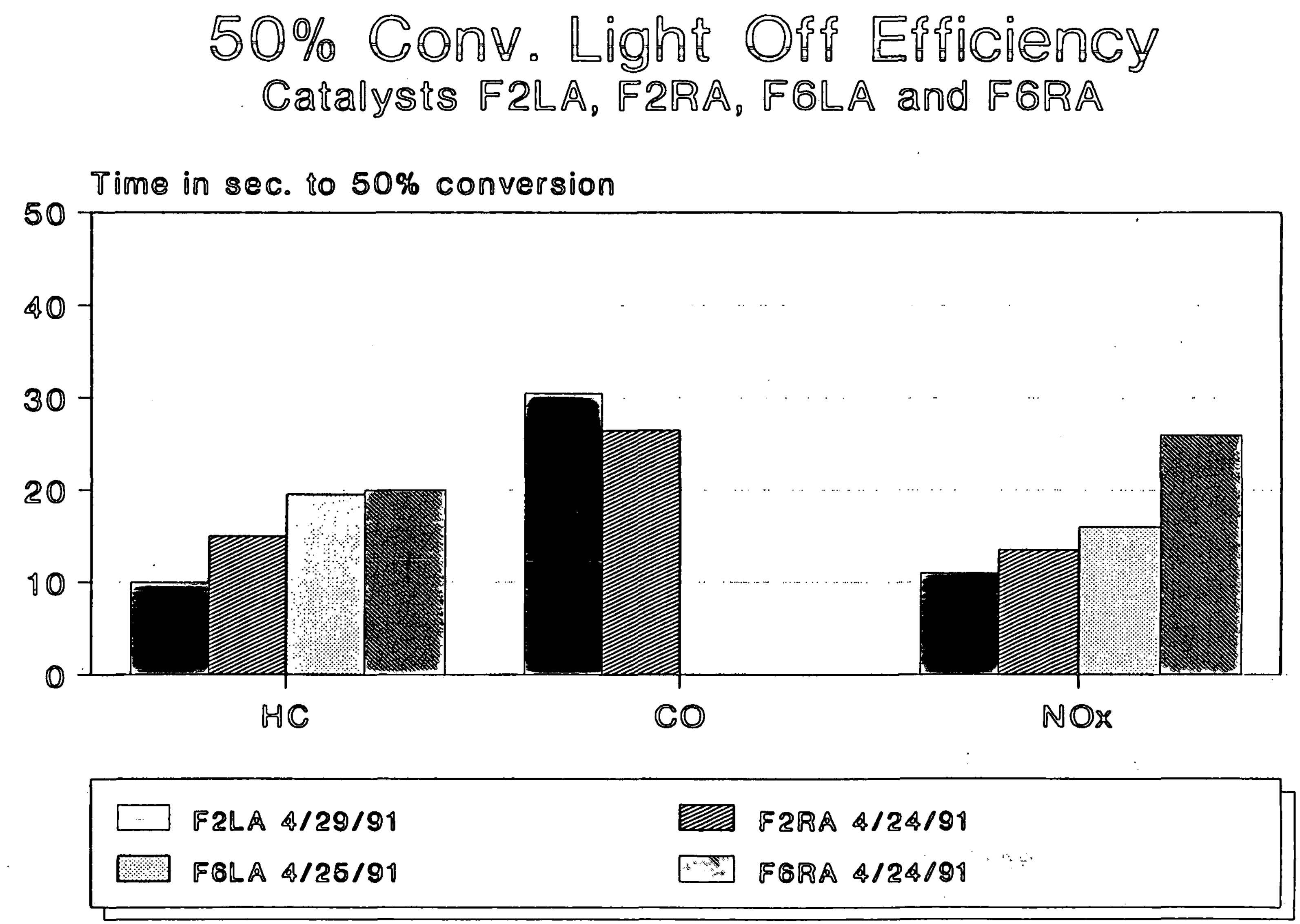


FIGURE 20. 50% LIGHT-OFF EFFICIENCY FOR CONVERTERS F2LA, F2RA, F6LA AND F6RA

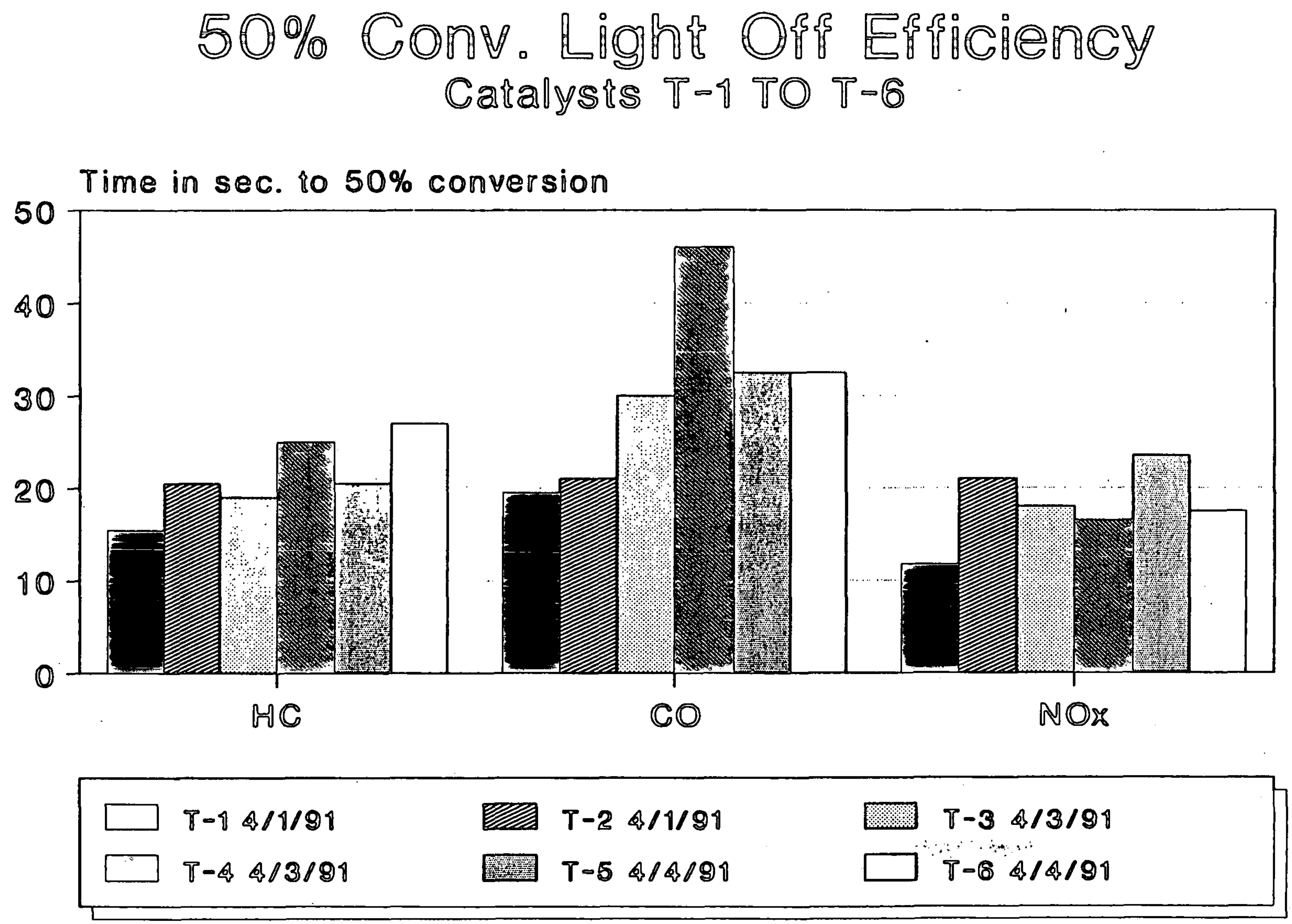


FIGURE 21. 50% LIGHT-OFF EFFICIENCY FOR CONVERTERS T-1 TO T-6

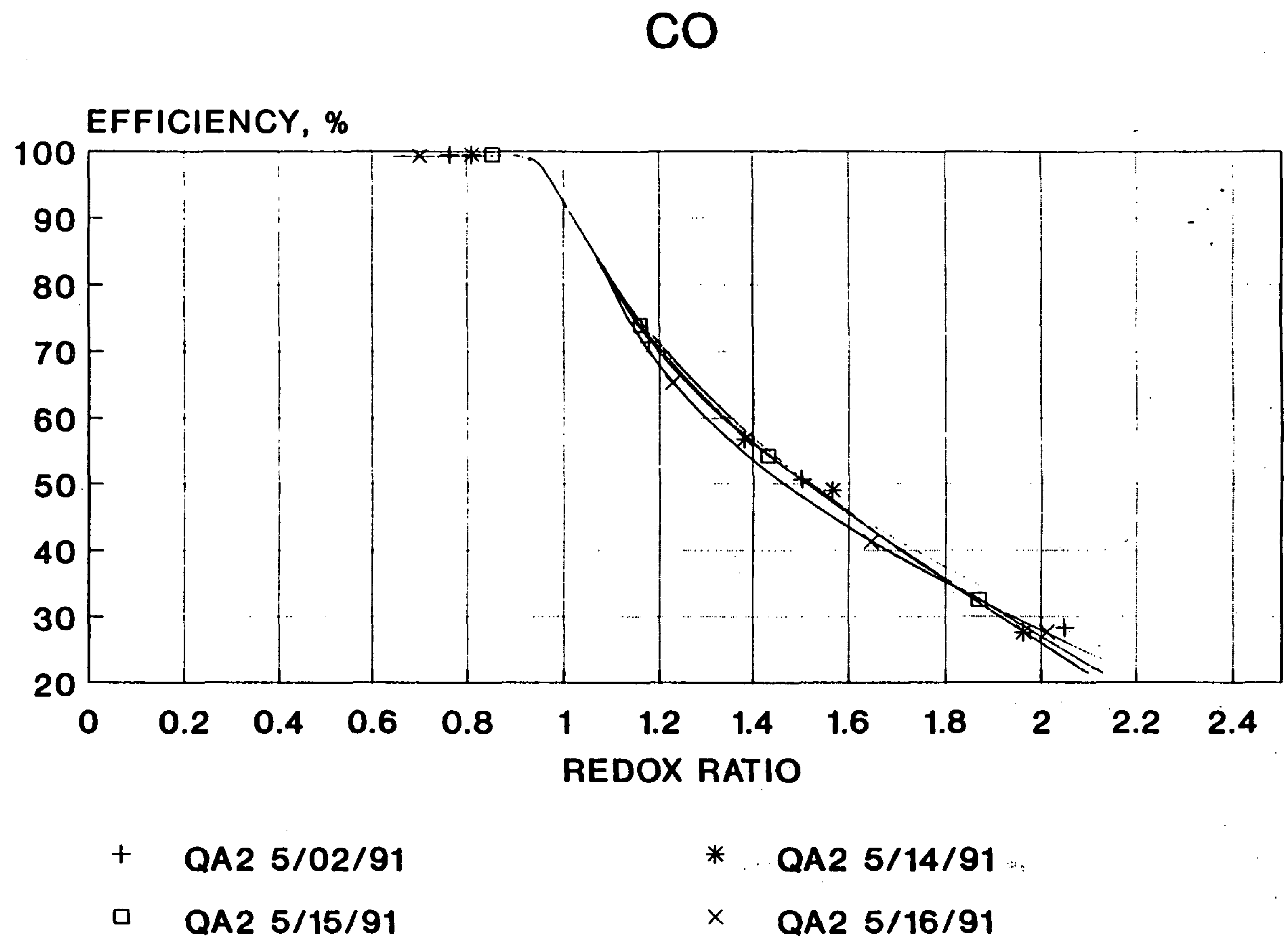


FIGURE 22. QA CONVERTER CO EFFICIENCIES

APPENDICES

APPENDIX A

PROJECT REQUEST AND SUPPORTING DOCUMENTS

SOUTHWEST RESEARCH INSTITUTE

6220 CULEBRA ROAD ° POST OFFICE DRAWER 28510 ° SAN ANTONIO, TEXAS, USA 78228-0510 ° (512) 684-5111 ° TELEX 244846

December 14, 1990

TO: Ethyl Corporation
Ethyl Tower
451 Florida Street
Baton Rouge, Louisiana 70801-1780

ATTN: Dr. Ben F. Fort
Health and Environmental Department

SUBJECT: SwRI Proposal 08-10993, "Evaluation of Used Catalytic Converters."

I. INTRODUCTION

This proposal is in response to your letter request of December 4, 1990, and subsequent telephone discussions. A copy of the letter and its attachments are included as Appendix A to this proposal. The work proposed herein will be conducted by the Department of Emissions Research (DER) of Southwest Research Institute (SwRI) at their laboratory in San Antonio, Texas.

The letter request divided the work up into three phases, with the work to be done in phases two and three dependent on the outcome of the work in phase one. Since a prompt response was desired and the work in Phases 2 and 3 is not completely defined at this time, this proposal covers Phase 1 only.

II. STATEMENT OF WORK

Used catalytic converters furnished by Ethyl Corporation will be evaluated for efficiency using a slave engine. The paragraphs below discuss the converters to be tested, slave engine, test cell, test procedures, and emissions to measured.

A. Converters to be Tested

Ethyl Corp. will furnish 20 used converters for testing. It is our understanding that the converters are from a variety of automobiles, but that they are in pairs, so that there will be a maximum of 10 different types of converters. One converter of each pair will be from a car operated using fuel with an MMT additive, and the other converter of each pair from a similar car using fuel without the MMT additive. We would prefer that the converters were coded so that we did not know which converter was which.

It is also our understanding that "many" of these converters have had the front diffuser section cut off very close to the first catalyst brick. This situation is of some concern.

In telephone conversations with Ethyl Corp. we have discussed possible fixes for the lack of entrance diffusers. These fixes have included various ways of attaching new entrance diffusers and the possibility of recanning the catalyst bricks. Since the results of these tests will be thoroughly scrutinized by a number of organizations, we think that it would be best to disturb the converters as little as possible before the efficiency tests. Therefore, we propose to fabricate and install new entrance diffusers for each of the converters before the converter efficiency tests. This will eliminate criticisms about possible leaks in temporary "quick fix" type diffusers, and possible criticisms about errors, damage, and thermal characteristics, if the catalyst bricks were recanned. For Phase 2 tests, however, the catalyst bricks must be recanned.

B. Converter Radiographs

Each converter will be radiographed (x-rayed) to determine the internal condition of the catalyst bricks. Radiographing whole converters has become routine at SwRI. This procedure enables substrate cracks, meltdowns, and movement to be identified without disassembling the converter.

C. Test Cell and Slave Engine

Testing will be conducted in Cell No. 6 of SwRI's Department of Emissions Research. A 350 CID Chevrolet gasoline engine is installed in the cell for light-off and efficiency evaluations. The load absorber for the engine is an eddy current dynamometer capable of absorbing up to 175 horsepower at 6000 rpm. The amount of engine exhaust that flows through the converter is adjustable, to permit a wide range of flow through the converter test section.

The engine is equipped with an aftermarket electronic throttle body fuel injection system, manufactured by Air Sensors Corp. of Seattle, Washington. This fuel injection system permits adjustment of the engine air fuel ratio over the operating range of the engine. SwRI has modified the fuel injection system electronics to permit the air fuel ratio to be cycled from rich to lean settings at frequencies from 0.25 to 2 hertz.

D. Fuel

The fuel used for these tests will be Howell EEE emission test gasoline.

E. Evaluation Tests Performed

The performance test on each converter will consist of a light-off test patterned after the GM "Cell 102 Test," and a warmed-up efficiency evaluation at 6 different Redox ratios.
The Redox ratio, R, is defined as shown below:

$$R = \frac{CO + H_2 + 3(HC)}{2(O_2) + NO}$$

The light-off test begins with the converter below 40 degrees C., and the engine exhaust bypassing the converter. For these tests the engine speed will be set at 1800 RPM, the Redox ratio will be set at 1.0, and the fuel cycled 0.5 A/F ratios about this Redox setting at a frequency of 1.0 hertz. When a stable engine exhaust temperature of 500 degrees C. is reached, the exhaust will be switched to flow through the converter using a quick-acting valve. Emission concentrations will be measured continuously before and after the converter, and the time to reach 50 percent and 75 percent conversion efficiency calculated.

The warmed-up efficiency evaluation will be conducted at the same engine RPM and exhaust temperature, but at six different Redox ratios. These Redox ratios are: 0.8, 1.0, 1.2, 1.4, 1.6, and 1.8.

F. Emissions Measured

Heated sample lines before and after the converter test section deliver exhaust samples to the emissions instrument cart. Two complete sets of emissions instrumentation are available at the cell for measuring emission concentrations before and after the catalytic converter being tested. To obtain the converter efficiencies, total HC, CO, and NO_x, will be measured before and after the converter. In addition, O_2 will be measured before and after the converter and CO_2 before the converter. Total hydrocarbons will measured by heated FID; CO and CO2 by NDIR; O_2 by polarographic instruments; and NOx by heated chemiluminesce.

Currently, there is no provision for measuring H_2 in the test cell. It would take considerable time, effort, and expense to provide such capability in the cell. At this time we are uncertain as to how the H_2 necessary for the Redox calculation will be obtained, but are proposing that it be estimated from other emissions.

G. Quality Assurance Tests

To provide evidence that the converters were all evaluated on the same feed gas composition and that the entire procedure is repeatable, three light-off and efficiency tests will be run using the cell QA standard converter. One test will be run before beginning the evaluations on the Ethyl converters, one test after 10 converters have been tested, and the final test at the completion of testing for all 20 converters. One converter, chosen at random, will be tested five times for light-off and efficiency at two different Redox ratios to define the test-to-test repeatability for this set of converters.

H. Test Chronology

Before testing can begin, a decision must be made as to how to repair the converters that have their entrance diffuser removed. Once this decision is made, the repairs can be initiated. It is not necessary that repairs on all converters be completed before testing begins. It is only necessary that sufficient converters have been repaired so that these will be a ready supply of converters to be tested. Once the converters have been repaired, the whole converter will radiographed (x-rayed).

After a sufficient number of converters have been repaired and radiographed, the converter testing can begin. The order of testing of the converters should perhaps be randomized for statistical reasons. On the other hand, Ethyl may desire back-to-back comparisons of the converter pairs. We will test the converters in any order desired; however, if no preference is expressed, we will test the converters in random order.

The test results will be compiled as the testing progresses. Preliminary data for a converter will be available to Ethyl within three days after it completes testing, if desired. At the completion of the testing a data-only letter final report will be sent to Ethyl Corp. with tables of test results for all converters.

III. SCHEDULE AND PRICE

Work cannot be scheduled until a signed contract and an initial payment are received. It is expected that this will occur before the end of December, 1990. Since many of the converters do not have a front diffuser cone, some preparation will be required before testing of the converters can begin. If a signed contract is received before the end of December 1990, we can begin work on repairing or recanning the catalysts; but because of holiday vacation schedules, it is not expected that the converters would be ready for testing before the second week in January. It is estimated that the work specified in Phase 1, as outlined above, can be completed within two months from the start of the project.

This work is proposed on a fixed price basis. The price for the work proposed is $53,500. This price includes all preparations, emissions sampling, and data reporting. A formal final report was not requested, and is not included in the price above.

IV. CLOSURE

It has been our pleasure to respond to your request for emission evaluations on 20 used catalytic converters. We have tried to make our response as complete as possible, but if you have any questions or need further information, please contact Mel Ingalls at (512) 522-2645. A contract for the proposed work is included as Appendix B of this proposal. If this proposal is satisfactory, please return the signed contract to Ms. Dorothy Rosales, Contract Administrator. Any questions of a contractual nature should be directed to Ms. Rosales at (512) 522-2230.

Prepared and Submitted by:

Melvin N. Ingalls

Melvin N. Ingalls
Senior Research Engineer
Department of Emissions Research
Automotive Products and Emissions
Research Division

Approved by:

Charles T. Hare

Charles T. Hare
Director
Department of Emissions Research
Automotive Products and Emissions
Research Division

cc: Bruce Bykowski

APPENDIX A

REQUEST FOR PROPOSAL

ETHYL CORPORATION
Health and Environment Department

Air Conservation

Ethyl Tower
451 Florida Street
Baton Rouge, LA 70801

December 4, 1990

Mr. Melvin N. Ingalls
Southwest Research Institute
6220 Culebra Road
San Antonio, Texas 78228-0510

Dear Mel:

Ethyl Corporation wants to conduct a catalyst testing program at SWRI in San Antonio. The following study parameters are desired:

- All catalysts to be evaluated using exhaust gas from one "slave" test engine.
- Engine fuel to be Howell EEE
- Conversion efficiency determinations made with cycles between rich and lean at frequency of 1Hz* with amplitude of about 0.5* units of A/F ratio.

The first phase of the study will involve 20 catalyst monoliths for "light-off" and steady state evaluations of conversion efficiency at redox ratios of 0.8, 1.0, 1.2, 1.4, 1.6 and 1.8 for the three pollutants, hydrocarbons, carbon monoxide and nitrogen oxide.

The second phase is to be considered as optional depending on the outcome of consultations with EPA and Ford on the results of Phase 1. The following work should be costed for Phase 2**:

- Repeats of Phase 1 after removal of last half of the monolith.
- Metals and surface area on the removed portion.
- Repeats of Phase 1 after removal of three fourths of the monolith.
- Metals and surface area on the removed portion.
- Metals and surface area on the remaining quarter.

*Please make recommendations for these parameters.
**Run conditions identical to Phase 1.

A third phase may be additional monoliths processed through Phases 1 and 2.

There are many details to be settled before starting work. Many of these details involve situations described in the SAE paper by Shulman et al (#820276) entitled "Comparison of Measured and Predicted Three-Way Catalyst Conversion Efficiencies under Dynamic Air-Fuel Ratio Conditions."

Sincerely,

Ben F. Fort, Jr.

Ben F. Fort, Jr., Ph.D.
Senior Mathematics
and Statistical Associate

BFF:cr
040BFF90

APPENDIX B

QA DOCUMENTATION

CATALYST INLET OXYGEN CONCENTRATIONS AND STANDARD DEVIATION

CONV.	RUN NO.	DATE	Air to Fuel Ratio						
			14.85	14.65	14.55	14.45	14.40	14.30	L/O 14.45
			O2 CONC.	O2 CONC.	O2 CONC.	O2 CONC.	O2 CONC.	O2 CONC.	O2 CONC.
B-7	1	4/12/91	0.59	0.42	0.35	0.27	0.25	0.19	0.32
B-7	2	5/6/91	0.75	0.50	0.45	0.35	0.34	0.30	0.35
B-8	1	4/16/91	0.64	0.47	0.37	0.33	0.30	0.25	0.35
B-8	2	5/09/91	0.68	0.45	0.38	0.33	0.30	0.25	0.33
B-9	1	4/17/91	0.66	0.44	0.40	0.32	0.29	0.24	0.28
B-10	1	4/16/91	0.64	0.48	0.35	0.31	0.30	0.24	0.36
B-10	2	5/6/91	0.68	0.50	0.43	0.36	0.32	0.28	0.38
B-11	1	4/17/91	0.64	0.44	0.37	0.30	0.27	0.21	0.31
B-12	1	4/16/91	0.64	0.48	0.37	0.32	0.25	0.21	0.30
B-12	2	5/13/91	0.68	0.45	0.40	0.33	0.30	0.28	0.38
B-13	1	3/11/91	0.49	0.35	0.35	0.30	0.25	0.20	0.35
B-13	2	3/25/91	0.69	0.52	0.47	0.40	0.37	0.32	0.35
B-13	3	3/29/91	0.69	0.50	0.48	0.40	0.35	0.30	0.37
B-14	1	3/8/91	0.44	0.40	0.32	0.30	0.27	0.22	0.42
B-14	2	3/26/91	0.64	0.49	0.44	0.40	0.35	0.30	0.40
B-14	3	3/29/91	0.69	0.52	0.44	0.35	0.32	0.30	0.40
E-1	1	3/1/91	0.44	0.27	0.32	0.20	0.16	0.37	0.35
E-1	2	3/21/91	0.57	0.37	0.35	0.27	0.27	0.20	0.25
E-1	3	3/28/91	0.64	0.42	0.35	0.27	0.25	0.20	0.25
E-1	4	4/23/91	0.59	0.44	0.32	0.27	0.22	0.22	0.27
E-2	1	3/4/91	0.40	0.37	0.30	0.27	0.20	0.17	0.40
E-2	2	3/22/91	0.59	0.44	0.37	0.30	0.35	0.30	0.35
E-2	3	3/26/91	0.64	0.44	0.37	0.32	0.27	0.27	0.30
E-2	4	3/28/91	0.62	0.47	0.40	0.35	0.32	0.30	0.35
E-3	1	4/10/91	0.58	0.41	0.32	0.32	0.25	0.26	0.25
E-4	1	4/10/91	0.67	0.40	0.35	0.26	0.24	0.20	0.25
E-5	1	4/11/91	0.59	0.40	0.31	0.25	0.22	0.17	0.27
E-6	1	4/11/91	0.62	0.44	0.35	0.30	0.25	0.17	0.32
E-6	2	4/11/91	0.62	0.44	0.35	0.30	0.25	0.17	0.32
F2LA	1	4/29/91	0.59	0.44	0.41	0.32	0.27	0.22	0.32
F2RA	1	4/24/91	0.69	0.44	0.44	0.32	0.30	0.27	0.30
F6LA	1	4/25/91	0.67	0.44	0.37	0.32	0.30	0.27	0.30
F6RA	1	4/24/91	0.67	0.49	0.37	0.32	0.30	0.27	0.32
T-1	1	4/1/91	0.64	0.49	0.37	0.35	0.32	0.25	0.31
T-2	1	4/1/91	0.64	0.49	0.40	0.35	0.30	0.22	0.35
T-3	1	4/03/91	0.64	0.47	0.35	0.27	0.27	0.25	0.32
T-4	1	4/03/91	0.64	0.47	0.35	0.27	0.27	0.25	0.25
T-5	1	4/4/91	0.74	0.44	0.35	0.27	0.27	0.20	0.24
T-6	1	4/4/91	0.64	0.42	0.36	0.30	0.25	0.22	0.25

MAX	0.75	0.52	0.48	0.40	0.37	0.37	0.42
MIN	0.40	0.27	0.30	0.20	0.16	0.17	0.24
AVG	0.62	0.45	0.37	0.31	0.28	0.24	0.32
ST DEV	0.07	0.05	0.04	0.04	0.04	0.05	0.05

MAX	0.75	0.52	0.48	0.40	0.35	0.30	0.40
MIN	0.58	0.40	0.31	0.25	0.22	0.17	0.24
AVG	0.65	0.46	0.38	0.31	0.28	0.25	0.31
ST DEV	0.04	0.03	0.04	0.04	0.03	0.04	0.05

NOTE: Highlighted type represents the most recent run for each converter.

All concentrations in ppm. Instrument Range: 0-5%.

CATALYST INLET CARBON DIOXIDE CONCENTRATIONS AND STANDARD DEVIATION

CONV.	RUN NO.	DATE	Air to Fuel Ratio						
			14.85	14.65	14.55	14.45	14.40	14.30	L/O 14.45
			CO2 CONC.	CO2 CONC.	CO2 CONC.	CO2 CONC.	CO2 CONC.	CO2 CONC.	CO2 CONC.
B-7	1	4/12/91	14.49	14.49	14.49	14.49	14.49	14.33	14.49
B-7	2	5/6/91	14.33	14.33	14.49	14.49	14.33	14.33	14.33
B-8	1	4/16/91	14.49	14.81	14.81	14.81	14.65	14.49	14.49
B-8	2	5/09/91	14.65	14.65	14.65	14.65	14.49	14.49	14.49
B-9	1	4/17/91	14.81	14.81	14.81	14.81	14.84	14.81	14.91
B-10	1	4/16/91	14.49	14.49	14.49	14.49	14.33	14.33	14.17
B-10	2	5/6/91	14.49	14.65	14.55	14.49	14.49	14.33	14.49
B-11	1	4/17/91	14.33	14.49	14.49	14.39	14.39	14.42	14.49
B-12	1	4/16/91	14.33	14.33	14.33	14.33	14.17	14.17	14.33
B-12	2	5/13/91	14.65	14.65	14.81	14.81	14.81	14.65	14.65
B-13	1	3/11/91	14.65	14.65	14.65	14.49	14.33	14.17	14.33
B-13	2	3/25/91	14.33	14.02	14.02	14.02	14.17	14.02	14.02
B-13	3	3/29/91	14.17	14.17	14.33	14.02	14.33	14.17	14.02
B-14	1	3/8/91	14.65	14.65	14.65	14.65	14.49	14.49	14.65
B-14	2	3/26/91	14.02	14.02	14.02	14.33	14.02	14.02	13.87
B-14	3	3/29/91	14.49	14.49	14.49	14.33	14.49	14.49	14.33
E-1	1	3/1/91	14.65	14.65	14.65	14.65	14.33	14.49	14.49
E-1	2	3/21/91	13.71	13.71	13.87	13.71	13.71	13.56	13.56
E-1	3	3/28/91	14.33	14.33	14.49	14.33	14.49	14.33	14.17
E-1	4	4/23/91	14.97	14.81	14.81	14.65	14.65	14.65	14.81
E-2	1	3/4/91	14.81	14.65	14.65	14.33	14.49	14.33	14.17
E-2	2	3/22/91	14.65	14.65	14.65	14.49	14.49	14.33	14.49
E-2	3	3/26/91	14.81	14.97	14.81	14.81	14.65	14.65	14.65
E-2	4	3/28/91	14.49	14.49	14.17	14.02	14.17	14.17	14.17
E-3	1	4/10/91	14.65	14.49	14.65	14.49	14.49	14.33	14.33
E-4	1	4/10/91	14.42	14.49	14.49	14.49	14.49	14.33	14.33
E-5	1	4/11/91	14.33	14.65	14.49	14.49	14.49	14.49	14.33
E-6	1	4/11/91	14.49	14.65	14.65	14.49	14.49	14.49	14.49
E-6	2	4/11/91	14.49	14.65	14.65	14.49	14.49	14.49	14.49
F2LA	1	4/29/91	14.49	14.49	14.49	14.49	14.49	14.49	14.49
F2RA	1	4/24/91	14.49	14.33	14.49	14.65	14.65	14.65	14.49
F6LA	1	4/25/91	14.02	14.02	14.17	14.17	14.17	14.17	14.02
F6RA	1	4/24/91	14.81	14.49	14.49	14.49	14.49	14.49	14.49
T-1	1	4/1/91	14.49	14.65	14.49	14.49	14.33	14.65	14.39
T-2	1	4/1/91	14.42	14.42	14.49	14.49	14.49	14.49	14.65
T-3	1	4/03/91	14.49	14.49	14.65	14.49	14.49	14.49	14.49
T-4	1	4/03/91	14.33	14.33	14.33	14.33	14.33	14.17	14.33
T-5	1	4/4/91	14.33	14.49	14.49	14.33	14.33	14.33	14.33
T-6	1	4/4/91	14.17	14.33	14.33	14.49	14.42	14.33	14.33

MAX	14.97	14.97	14.81	14.81	14.84	14.81	14.91
MIN	13.71	13.71	13.87	13.71	13.71	13.56	13.56
AVG	14.47	14.48	14.50	14.45	14.42	14.37	14.37
ST DEV	0.24	0.25	0.22	0.23	0.20	0.22	0.25

MAX	14.97	14.81	14.81	14.81	14.84	14.81	14.91
MIN	14.02	14.02	14.17	14.02	14.17	14.17	14.02
AVG	14.47	14.49	14.51	14.46	14.46	14.43	14.42
ST DEV	0.21	0.18	0.17	0.19	0.16	0.17	0.20

NOTE: Highlighted type represents the most recent run for each converter.

All concentrations in ppm. Instrument Range: 0-16%.

CATALYST INLET NITROGEN OXIDES CONCENTRATIONS AND STANDARD DEVIATION

CONV.	RUN NO.	DATE	Air to Fuel Ratio 14.85 NOx CONC.	14.65 NOx CONC.	14.55 NOx CONC.	14.45 NOx CONC.	14.40 NOx CONC.	14.30 NOx CONC.	L/O 14.45 NOx CONC.
B-7	1	4/12/91	1174.41	1197.29	1185.86	1128.26	1162.92	1116.64	1254.00
B-7	2	5/6/91	1622.35	1588.39	1565.89	1510.03	1487.80	1487.80	1554.68
B-8	1	4/16/91	1343.57	1298.93	1276.51	1242.71	1220.05	1197.29	1265.26
B-8	2	5/09/91	1310.12	1276.51	1185.86	1185.86	1162.92	1116.64	1197.29
B-9	1	4/17/91	1365.81	1276.51	1272.01	1254.00	1244.97	1185.86	1231.39
B-10	1	4/16/91	1416.84	1410.19	1310.12	1298.93	1310.12	1265.26	1321.28
B-10	2	5/6/91	1521.17	1510.03	1498.91	1487.80	1476.70	1454.52	1543.49
B-11	1	4/17/91	1247.22	1220.05	1231.39	1162.92	1116.64	1069.78	1208.68
B-12	1	4/16/91	1339.12	1376.92	1321.28	1310.12	1254.00	1254.00	1287.73
B-12	2	5/13/91	1254.00	1254.00	1242.71	1208.68	1197.29	1197.29	1220.05
B-13	1	3/11/91	1139.85	1104.98	1104.98	1081.55	1034.24	1010.35	1116.64
B-13	2	3/25/91	1388.01	1343.57	1276.51	1254.00	1242.71	1208.68	1254.00
B-13	3	3/29/91	1577.13	1521.17	1487.80	1443.43	1421.27	1376.92	1432.35
B-14	1	3/8/91	1399.10	1376.92	1332.43	1310.12	1276.51	1220.05	1321.28
B-14	2	3/26/91	1287.73	1276.51	1265.26	1231.39	1231.39	1197.29	1254.00
B-14	3	3/29/91	1668.15	1633.74	1588.39	1547.97	1543.49	1521.17	1577.13
E-1	1	3/1/91	1174.41	1128.26	1185.86	1093.29	1081.55	1298.93	1487.80
E-1	2	3/21/91	1116.64	1069.78	1010.35	998.34	1046.13	1010.35	1034.24
E-1	3	3/28/91	1197.29	1162.92	1128.26	1139.85	1116.64	1081.55	1128.26
E-1	4	4/23/91	1321.28	1276.51	1231.39	1220.05	1162.92	1139.85	1104.98
E-2	1	3/4/91	1465.61	1376.92	1343.57	1343.57	1276.51	1242.71	1057.98
E-2	2	3/22/91	1532.32	1521.17	1487.80	1476.70	1487.80	1454.52	1487.80
E-2	3	3/26/91	1231.39	1174.41	1151.40	1104.98	1081.55	1069.78	1116.64
E-2	4	3/28/91	1185.86	1162.92	1069.78	1046.13	1057.98	1057.98	1057.98
E-3	1	4/10/91	1443.43	1432.35	1376.92	1354.70	1298.93	1276.51	1410.19
E-4	1	4/10/91	1399.10	1321.28	1287.73	1242.71	1231.39	1174.41	1265.26
E-5	1	4/11/91	1069.78	1057.98	1034.24	1022.31	1022.31	998.34	1069.78
E-6	1	4/11/91	1174.41	1151.40	1139.85	1081.55	1093.29	1034.24	1081.55
E-6	2	4/11/91	1174.41	1151.40	1139.85	1081.55	1093.29	1034.24	1081.55
F2LA	1	4/29/91	1668.15	1611.00	1611.00	1554.68	1543.49	1521.17	1577.13
F2RA	1	4/24/91	1276.51	1242.71	1242.71	1185.86	1162.92	1151.40	1151.40
F6LA	1	4/25/91	1254.00	1197.29	1139.85	1093.29	1093.29	1081.55	1104.98
F6RA	1	4/24/91	1242.71	1208.68	1174.41	1220.05	1185.86	1162.92	1185.86
T-1	1	4/1/91	1611.00	1611.00	1577.13	1543.49	1565.89	1510.03	1554.68
T-2	1	4/1/91	1622.35	1588.39	1577.13	1565.89	1554.68	1521.17	1588.39
T-3	1	4/03/91	1354.70	1287.73	1265.26	1265.26	1242.71	1231.39	1265.26
T-4	1	4/03/91	1365.81	1332.43	1298.93	1242.71	1162.92	1151.40	1162.92
T-5	1	4/4/91	1376.92	1421.27	1343.57	1265.26	1276.51	1242.71	1298.93
T-6	1	4/4/91	1432.35	1421.27	1432.35	1343.57	1376.92	1354.70	1410.19

MAX	1668.15	1633.74	1611.00	1565.89	1565.89	1521.17	1588.39
MIN	1069.78	1057.98	1010.35	998.34	1022.31	998.34	1034.24
AVG	1352.44	1322.43	1292.19	1260.09	1246.11	1222.60	1274.95
ST DEV	159.39	159.64	159.34	158.03	157.85	156.52	169.28

MAX	1668.15	1633.74	1611.00	1565.89	1565.89	1521.17	1588.39
MIN	1069.78	1057.98	1034.24	1022.31	1022.31	998.34	1057.98
AVG	1390.18	1358.53	1328.13	1293.68	1278.46	1250.82	1302.27
ST DEV	166.44	166.13	171.66	167.00	170.20	169.79	181.33

NOTE: Highlighted type represents the most recent run for each converter.

All concentrations in ppm. Instrument Range: 0-2500 ppm.

CATALYST INLET CARBON MONOXIDE CONCENTRATIONS AND STANDARD DEVIATION

CONV.	RUN NO.	DATE	Air to Fuel Ratio 14.85 CO CONC.	14.65 CO CONC.	14.55 CO CONC.	14.45 CO CONC.	14.40 CO CONC.	14.30 CO CONC.	L/O 14.45 CO CONC.
B-7	1	4/12/91	2176.71	3541.58	4518.76	6257.56	6332.02	8329.17	5522.08
B-7	2	5/6/91	2379.96	4518.76	5522.08	7779.93	8092.76	9127.86	7162.60
B-8	1	4/16/91	2583.58	4237.16	5449.43	6526.44	7162.60	8567.09	6257.56
B-8	2	5/09/91	2176.71	4448.16	5232.43	6706.95	7469.86	9047.28	6706.95
B-9	1	4/17/91	2109.03	4307.37	4845.25	6376.79	7086.22	8726.51	6706.95
B-10	1	4/16/91	2312.18	3957.57	5814.29	6257.56	7010.01	8567.09	6183.26
B-10	2	5/6/91	2217.34	3679.82	4873.79	6212.96	7469.86	8966.85	6109.13
B-11	1	4/17/91	2041.37	3887.96	5304.61	5887.75	6556.46	8567.09	5667.86
B-12	1	4/16/91	2109.03	3129.14	4802.50	5741.00	6706.95	8408.31	5814.29
B-12	2	5/13/91	2176.71	3818.47	5160.40	6035.17	7162.60	8487.62	5887.75
B-13	1	3/11/91	3129.14	4027.29	4307.37	4589.49	5522.08	6035.17	3957.57
B-13	2	3/25/91	2992.33	4448.16	6481.47	7936.00	8408.31	9696.03	7315.88
B-13	3	3/29/91	1906.11	4945.22	5449.43	6706.95	7547.12	8886.58	7010.01
B-14	1	3/8/91	5741.00	3957.57	4237.16	4945.22	5376.94	6183.26	3541.58
B-14	2	3/26/91	2855.82	5160.40	6109.13	7547.12	8014.30	9614.44	7315.88
B-14	3	3/29/91	2992.33	4307.37	5304.61	7086.22	7779.93	8408.31	7315.88
E-1	1	3/1/91	3060.70	4448.16	4097.12	5160.40	5522.08	3266.26	6631.62
E-1	2	3/21/91	2244.43	3887.96	4518.76	5814.29	6406.66	8171.40	5961.38
E-1	3	3/28/91	1973.73	3957.57	4448.16	5887.75	6481.47	7702.15	6257.56
E-1	4	4/23/91	2109.03	3679.82	5016.80	6257.56	7469.86	7936.00	6257.56
E-2	1	3/4/91	3472.61	3679.82	4237.16	4377.70	5160.40	5594.89	3403.74
E-2	2	3/22/91	2244.43	3679.82	4518.76	6406.66	7315.88	8567.09	6631.62
E-2	3	3/26/91	2244.43	4237.16	5667.86	6858.13	7392.78	8886.58	6858.13
E-2	4	3/28/91	2855.82	4237.16	5522.08	6706.95	7162.60	9047.28	6556.46
E-3	1	4/10/91	2447.79	4377.70	5232.43	6035.17	7624.55	8408.31	7010.01
E-4	1	4/10/91	1973.73	4027.29	4945.22	6183.26	6782.45	8567.09	6257.56
E-5	1	4/11/91	2176.71	3060.70	5203.60	5961.38	6481.47	8487.62	5449.43
E-6	1	4/11/91	2176.71	3541.58	4660.35	5814.29	6332.02	8567.09	5814.29
E-6	2	4/11/91	2176.71	3541.58	4660.35	5814.29	6332.02	8567.09	5814.29
F2LA	1	4/29/91	2352.84	4097.12	4945.22	6257.56	7469.86	8487.62	6481.47
F2RA	1	4/24/91	2176.71	4448.16	5016.80	7010.01	7315.88	8886.58	7162.60
F6LA	1	4/25/91	2176.71	3887.96	5522.08	5814.29	7162.60	8567.09	6631.62
F6RA	1	4/24/91	2041.37	3887.96	5376.94	6481.47	7010.01	8408.31	6257.56
T-1	1	4/1/91	2651.55	3957.57	5376.94	6556.46	6933.98	7624.55	7162.60
T-2	1	4/1/91	2515.66	4237.16	5016.80	5961.38	6706.95	8567.09	6257.56
T-3	1	4/03/91	2041.37	3679.82	5088.52	6257.56	6706.95	8092.76	6257.56
T-4	1	4/03/91	2041.37	3610.65	5088.52	7779.93	7010.01	7779.93	7624.55
T-5	1	4/4/91	2109.03	3749.09	4589.49	7162.60	7239.15	8329.17	6556.46
T-6	1	4/4/91	2217.34	4307.37	5232.43	7010.01	6933.98	8092.76	7010.01

	14.85	14.65	14.55	14.45	14.40	14.30	L/O 14.45
MAX	5741.00	5160.40	6481.47	7936.00	8408.31	9696.03	7624.55
MIN	1906.11	3060.70	4097.12	4377.70	5160.40	3266.26	3403.74
AVG	2445.64	4015.16	5061.41	6311.85	6939.79	8210.85	6276.43
ST DEV	649.23	425.29	513.07	779.61	714.25	1145.89	933.40

	14.85	14.65	14.55	14.45	14.40	14.30	L/O 14.45
MAX	2992.33	4945.22	5522.08	7779.93	8092.76	9127.86	7624.55
MIN	1906.11	3060.70	4589.49	5814.29	6332.02	7624.55	5449.43
AVG	2252.64	4029.18	5146.95	6501.77	7146.13	8502.81	6554.77
ST DEV	264.50	396.84	253.86	555.77	420.61	385.86	545.94

NOTE: Highlighted type represents the most recent run for each converter.

All concentrations in ppm. Instrument Range: 0-15000 ppm.

CATALYST INLET HYDROCARBON CONCENTRATIONS AND STANDARD DEVIATION

CONV.	RUN NO.	DATE	Air to Fuel Ratio 14.85 HC CONC.	14.65 HC CONC.	14.55 HC CONC.	14.45 HC CONC.	14.40 HC CONC.	14.30 HC CONC.	L/O 14.45 HC CONC.
B-7	1	4/12/91	49.85	94.72	144.57	219.34	224.33	311.56	186.94
B-7	2	5/6/91	99.70	224.33	261.71	373.88	386.34	423.73	348.95
B-8	1	4/16/91	67.30	152.04	211.86	254.24	299.10	353.94	249.25
B-8	2	5/09/91	87.24	211.86	249.25	361.41	411.26	448.65	373.88
B-9	1	4/17/91	69.79	174.48	211.86	286.64	311.56	396.31	299.10
B-10	1	4/16/91	62.31	137.09	236.79	249.25	274.18	348.95	261.71
B-10	2	5/6/91	82.25	162.01	236.79	286.64	348.95	411.26	261.71
B-11	1	4/17/91	57.33	149.55	224.33	249.25	286.64	373.88	254.24
B-12	1	4/16/91	52.34	112.16	186.94	224.33	261.71	348.95	224.33
B-12	2	5/13/91	87.24	174.48	286.64	311.56	373.88	423.73	324.03
B-13	1	3/11/91	249.25	324.03	324.03	373.88	423.73	448.65	324.03
B-13	2	3/25/91	137.09	286.64	324.03	274.18	311.56	498.50	286.64
B-13	3	3/29/91	119.64	174.48	214.36	274.18	324.03	373.88	286.64
B-14	1	3/8/91	274.18	336.49	348.95	386.34	436.19	498.50	274.18
B-14	2	3/26/91	124.63	229.31	286.64	348.95	361.41	461.11	361.41
B-14	3	3/29/91	129.61	191.92	239.28	311.56	348.95	373.88	348.95
E-1	1	3/1/91	124.63	179.46	171.98	199.40	224.33	149.55	299.10
E-1	2	3/21/91	74.78	149.55	199.40	274.18	299.10	373.88	274.18
E-1	3	3/28/91	62.31	162.01	186.94	261.71	286.64	336.49	249.25
E-1	4	4/23/91	74.78	137.09	199.40	274.18	311.56	336.49	249.25
E-2	1	3/4/91	174.48	149.55	174.48	174.48	199.40	211.86	124.63
E-2	2	3/22/91	49.85	137.09	174.48	274.18	299.10	324.03	299.10
E-2	3	3/26/91	62.31	162.01	249.25	299.10	324.03	373.88	274.18
E-2	4	3/28/91	99.70	174.48	249.25	299.10	324.03	398.80	299.10
E-3	1	4/10/91	54.84	124.63	174.48	211.86	274.18	311.56	254.24
E-4	1	4/10/91	39.88	124.63	174.48	211.86	249.25	324.03	211.86
E-5	1	4/11/91	37.39	74.78	174.48	199.40	224.33	311.56	186.94
E-6	1	4/11/91	37.39	99.70	162.01	211.86	224.33	324.03	199.40
E-6	2	4/11/91	37.39	99.70	162.01	211.86	224.33	324.03	199.40
F2LA	1	4/29/91	87.24	174.48	224.33	286.64	324.03	373.88	286.64
F2RA	1	4/24/91	62.31	162.01	211.86	286.64	299.10	373.88	299.10
F6LA	1	4/25/91	84.75	154.54	231.80	279.16	314.06	386.34	299.10
F6RA	1	4/24/91	67.30	147.06	224.33	286.64	304.09	363.91	274.18
T-1	1	4/1/91	87.24	149.55	219.34	274.18	299.10	324.03	311.56
T-2	1	4/1/91	87.24	174.48	211.86	236.79	299.10	373.88	261.71
T-3	1	4/03/91	74.78	149.55	199.40	299.10	299.10	361.41	286.64
T-4	1	4/03/91	62.31	124.63	186.94	336.49	299.10	361.41	324.03
T-5	1	4/4/91	49.85	124.63	174.48	286.64	299.10	336.49	249.25
T-6	1	4/4/91	49.85	137.09	179.46	286.64	261.71	324.03	254.24

	14.85	14.65	14.55	14.45	14.40	14.30	L/O 14.45
MAX	274.18	336.49	348.95	386.34	436.19	498.50	373.88
MIN	37.39	74.78	144.57	174.48	199.40	149.55	124.63
AVG	86.98	164.31	218.06	275.58	303.77	363.46	272.64
STD DEV	50.74	54.69	46.98	50.78	54.55	64.58	50.92

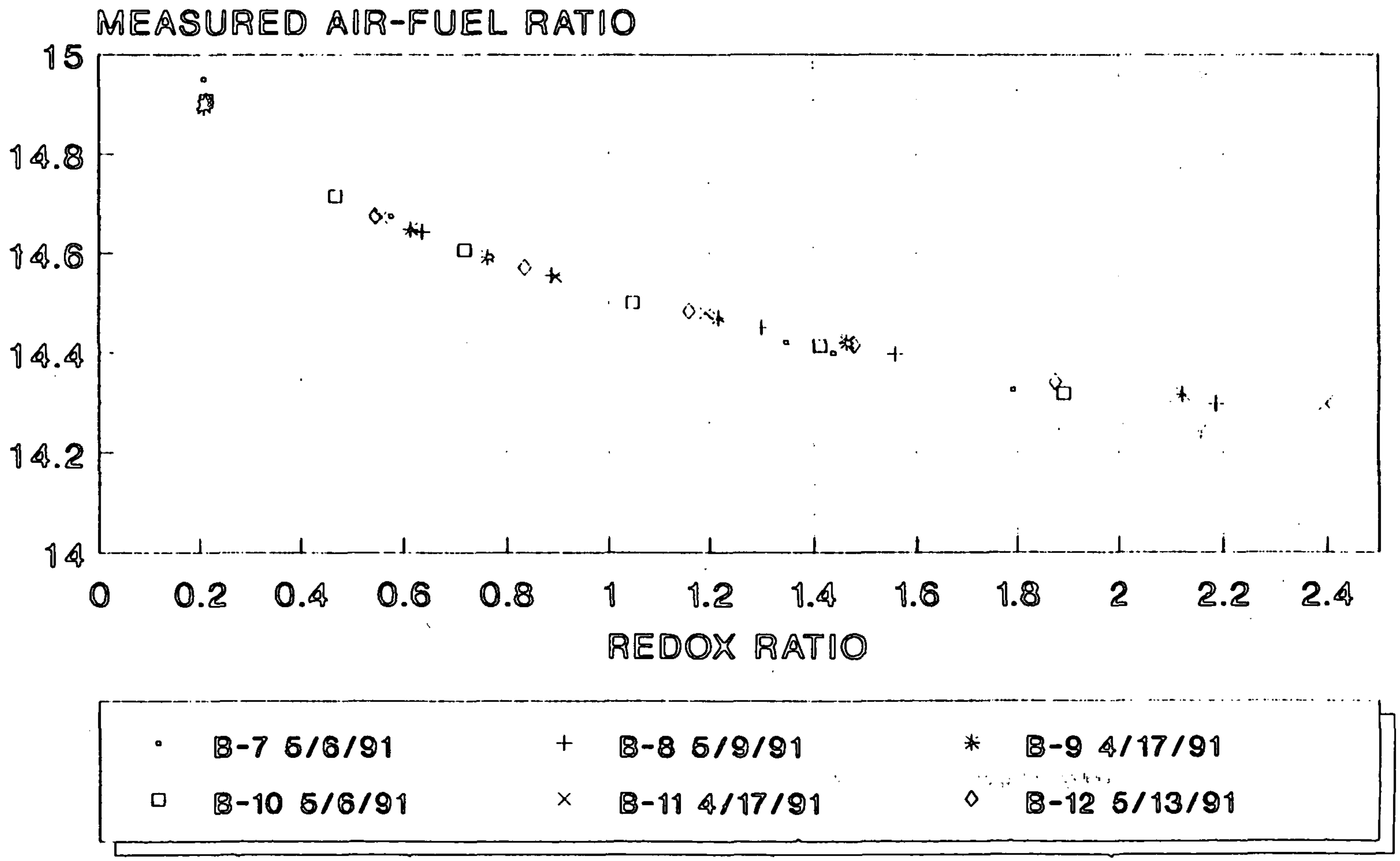
	14.85	14.65	14.55	14.45	14.40	14.30	L/O 14.45
MAX	129.61	224.33	286.64	373.88	411.26	448.65	373.88
MIN	37.39	74.78	162.01	199.40	224.33	311.56	186.94
AVG	74.57	154.02	213.42	280.09	308.24	367.12	281.03
STD DEV	23.75	32.74	31.07	43.30	44.26	37.11	45.25

NOTE: Highlighted type represents the most recent run for each converter.

All concentrations in ppm. Instrument Range: 0–2500 ppm.

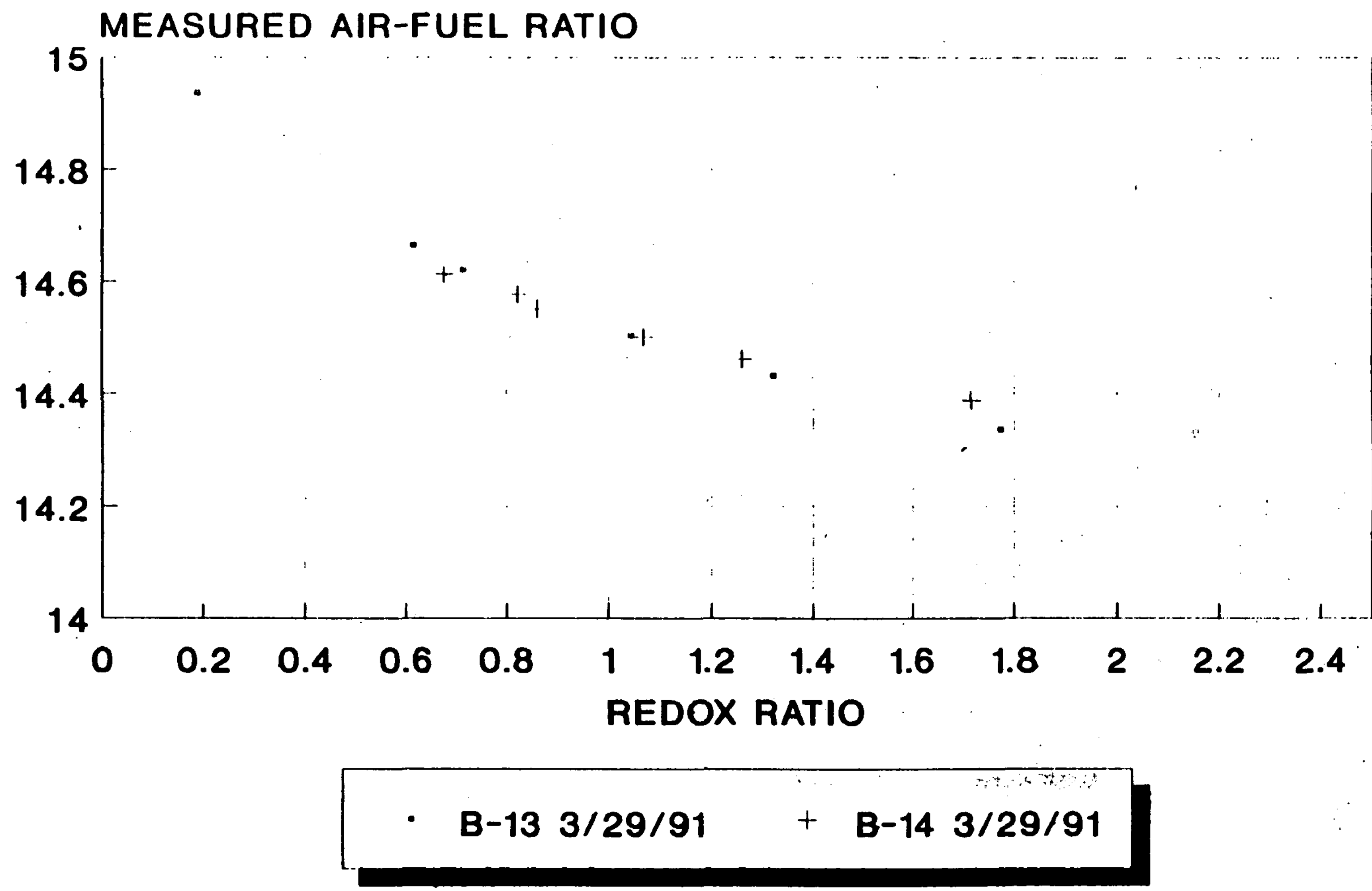
A/F RATIO

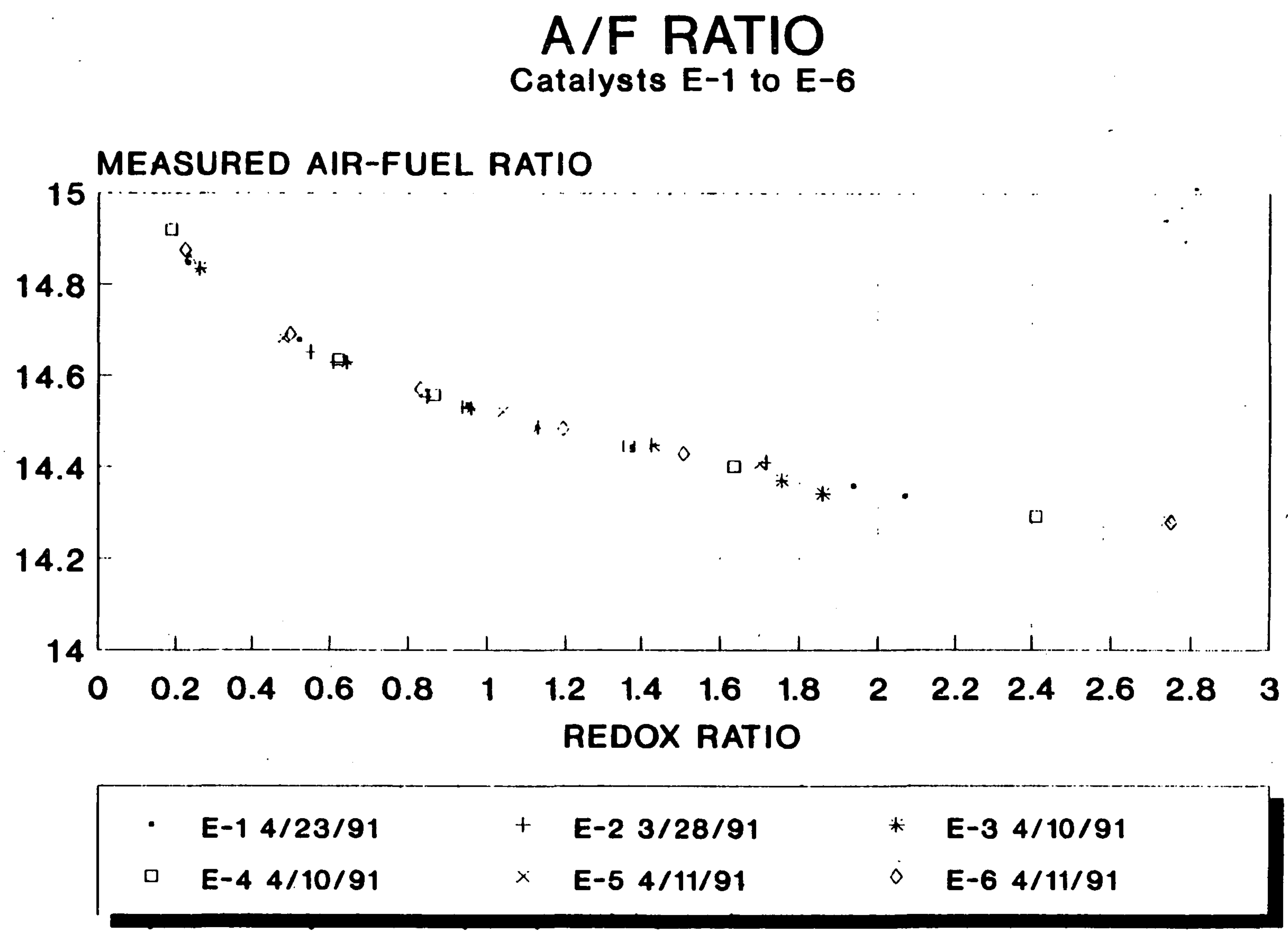
Catalysts B-7 TO B-12



A/F RATIO

Catalysts B-13 to B-14





A/F RATIO
Catalysts E-1 to E-6
MEASURED AIR-FUEL RATIO
15
14.8
14.6
14.4
14.2
14
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
REDOX RATIO
E-1 4/23/91
E-2 3/28/91
E-3 4/10/91
E-4 4/10/91
E-5 4/11/91
E-6 4/11/91